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The Golden Age of Cataclysmic Variables and Related Objects (An Updated Review)

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The body of this review is essentially that reported in Giovannelli (2021b). There are additions that make the review up to date especially with the numerous references added.
This review article arises from what was presented by me as the introductory speech of the workshop "The Golden Age of Cataclysmic Variables and Related Objects - VI". Obviously for reasons of space and my limited knowledge this article will be subject to selective choices of the topics covered. However, it is my intention to provide the reader with a personal overview of the problems solved and to be solved in this fascinating field of the cataclysmic variables. Far be it from me to claim to have treated the topic comprehensively.

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1. Introduction

The advent of space experiments, which can be dated approximately to the early 1970s, practically opened new windows of observation of the Universe that cover the entire range of the electromagnetic spectrum. Fig. 1 schematically shows the amount of data acquired through the use of space experiments since the 1970s. It may be noted that the amount of this data far exceeds that acquired by ground-based optical telescopes since the beginning of astronomy. A general problem that arises from the possession of this immense quantity of data is that of their analysis and their use in order to find a synthesis.

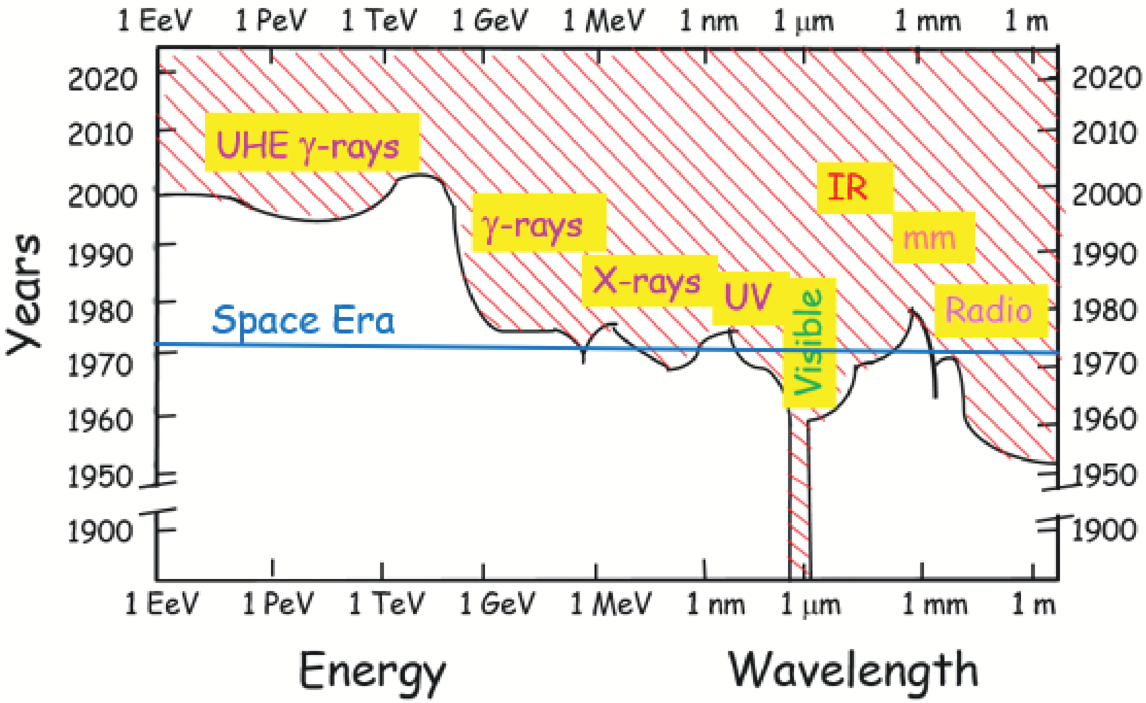


Figure 1: Amount of astronomical data acquired across the electromagnetic spectrum (updated from Giovannelli & Sabau-Graziati, 2004, after Lena, 1988)

All the stars are practically variables with different level of variations in luminosity and in time. It is possible to distinguish variable stars in two categories:

- **Intrinsic variable stars** in which the mechanisms that cause luminosity variations involve the physical properties of the stars.
- **Extrinsic variable stars** in which the mechanisms that cause luminosity variations involve extrinsic factors such as a companion star that eclipses a "normally relatively stable star" periodically.

Figure 2 shows an interesting classification of variable stars in Group, Class, and Type (Christoforou, 2017)).

This is a convenient classification that however masks the real continuity among all the variable stars. Indeed, in nature everything is linked with different strength of the connections. In fact there

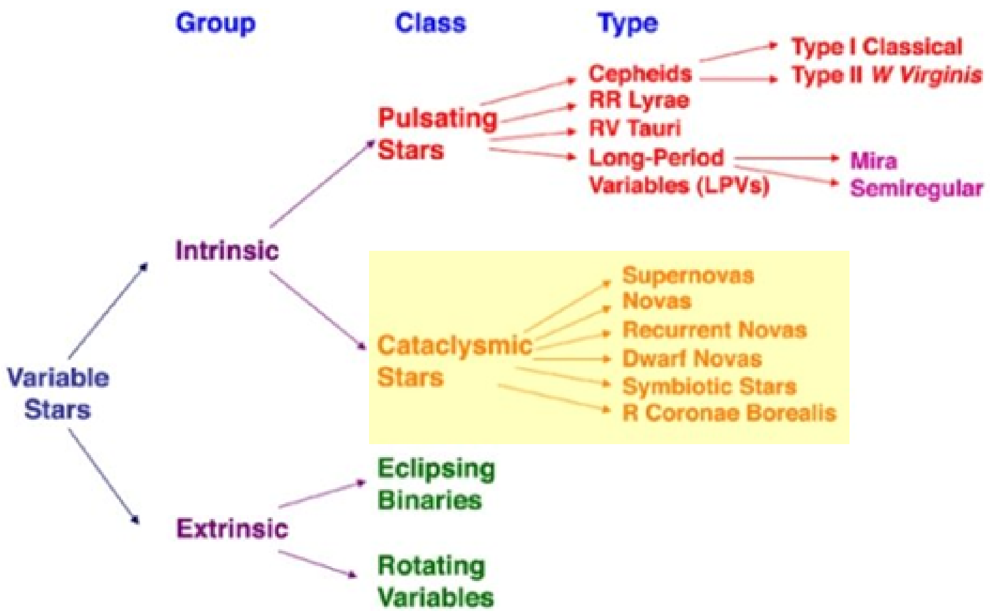


Figure 2: Variable stars: Group, Class, and Type (adapted from Christoforou, 2017). Light yellow rectangle marks the cataclysmic stars.

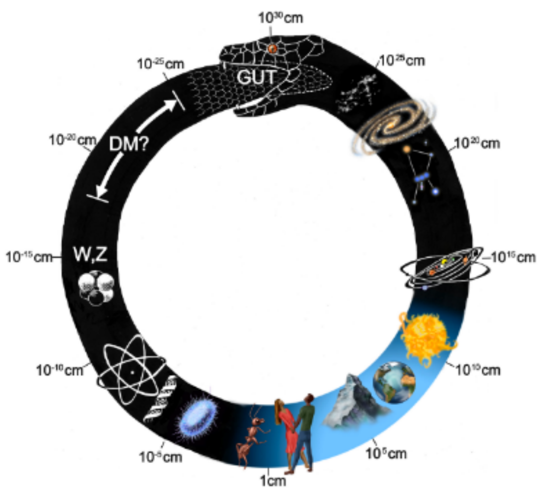


Figure 3: From the infinitely small to infinitely big (adopted from Giovannelli & Sabau-Graziati, 2017a after Rees, 1988).

is a *Bridge between the Big Bang and Biology*. Indeed, independent of the origin of our Universe, we are here in this planet. This is the demonstration that the bridge really exists (Giovannelli, 2001).

Therefore two fundamental questions arise: i) How to cross this Bridge? ii) What are the experimental tools for understanding the pillars of this Bridge?

In order to cross this bridge, as always when we cross a bridge, we MUST advance slowly, step by step, with continuity, because everything is smoothly linked in the "magma" of the Universe, from the infinitely small to infinitely big, as sketched in Fig. 3 (adopted from Giovannelli & Sabau-Graziati, 2017a after Rees, 1988).

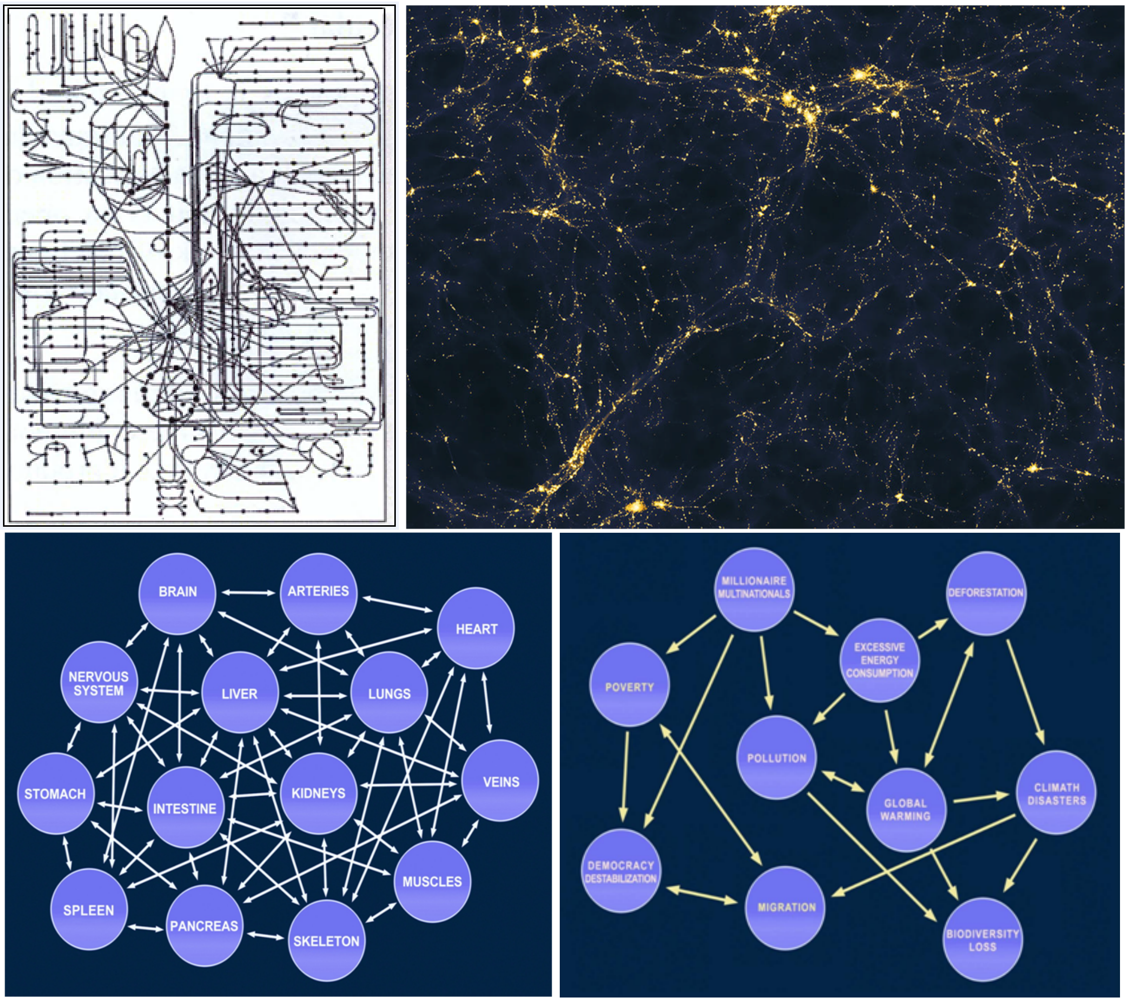


Figure 4: Upper left panel: Section of the metabolic network of a "simple" bacterium (Luisi & Capra, 2014). Upper right panel: the "cosmic network" [Credit: Andrew Pontzen and Fabio Governato, 2014; https://www.flickr.com/photos/uclmaps/15051460475/]. Lower left panel: the human body network. Lower right panel: the human society network (Luisi & Capra, 2014).

In nature, nothing is isolated. Everything is related to the surrounding environment in a more or less strong way. However, the link exists. Fig 4 (upper left) shows a section of the metabolic network of a "simple" bacterium. Note that each point (each chemical compound) is connected to any other point through the complexity of the network (Luisi & Capra, 2014). Fig. 4 (Upper right) shows the cosmic network: each point is connected to any other point through the complexity of the network (Credit: Andrew Pontzen and Fabio Governato, 2014; https://www.flickr.com/photos/uclmaps/15051460475/). The large-scale structure of the Universe, as traced by the distribution of galaxies, is now being revealed by large-volume cosmological surveys. The structure is characterized by galaxies distributed along filaments, the filaments connecting in turn to form a percolating network. This image is a computer simulation of an area of space more than 50 million light-years across, presenting a possible large-scale distribution of light sources in the universe. Precise relative contributions of galaxies and quasars are unclear. The objective of

Shandarin, Habib & Heitmann (2010) was to quantitatively specify the underlying mechanisms that drive the formation of the cosmic network. By combining percolation-based analyzes with N-body simulations of gravitational structure formation, they elucidate how the network has its origin in the properties of the initial density field (nature) and how its contrast is then amplified by the nonlinear mapping induced by the gravitational instability (nurture).$^{(*)}$

$^{(*)}$ In statistical physics and mathematics, percolation theory describes the behavior of a network when nodes or links are removed. This is a type of phase transition, since at a critical fraction of removal the network breaks into significantly smaller connected clusters. The percolation threshold is a mathematical concept in percolation theory that describes the formation of long-range connectivity in random systems. Below the threshold a giant connected component does not exist; while above it, there exists a giant component of the order of system size. Percolation theory has been used in astrophysics before the study of the large-scale structure in the Universe as a way to characterize voids, walls, and filamentary structure, an analogy explored early in the history of gravitational instability theory (Shandarin,1983) and more recently in the context of modern structure formation theory (e.g. Sahni, Sathyaprakash & Shandarin, 1997; Shandarin et al., 2006; Shandarin, Habib & Heitmann, 2010; Falck & Neyrinck, 2015). In that case, it is useful in describing the distribution of low-density regions, but the filling factor of those regions (the quantity of most interest in percolation processes) is only indirectly observable through its implications for the galaxy distribution. However, it is possible to see that many of the results of these studies are relevant to the percolation of ionized structures during reionization (Furlanetto & Oh, 2016).

Fig. 4 (Lower left) shows the human body network: each point (organ) is connected to any other point (organ) through the complexity of the network (Luisi & Capra, 2014). Fig. 4 (Lower right) shows the human society network: each point is connected to any other point through the complexity of the network (Luisi & Capra, 2014).

All the components of the Universe follow the cycle: birth, growth, aging, death like Humans that belong to the Universe. Therefore for a complete understanding of the history of the Universe it is necessary to search along that cycle.

In the long review published by Giovannelli (2017b) an exhaustive discussion about the importance of considering CVs as gravimagnetic rotators was reported, as well as the hints for considering all the CVs as a manifestation of physical conditions of binary systems smoothly connected along their evolutionary path, independent of the popular classification in Polar (Ps), Intermediate Polars (IPs) and non-magnetic CVs (NMCVs).

The old cataclysmic variable (CVs) classification was based on the optical outburst properties, by which one may distinguish four groups:

- Classical novae.
- Recurrent novae.
- Dwarf novae.
- Nova-like objects.

This classification, however, is neither self-consistent nor adequate and it is much better to consider primarily the observed accretion behaviour (Smak, 1985a).

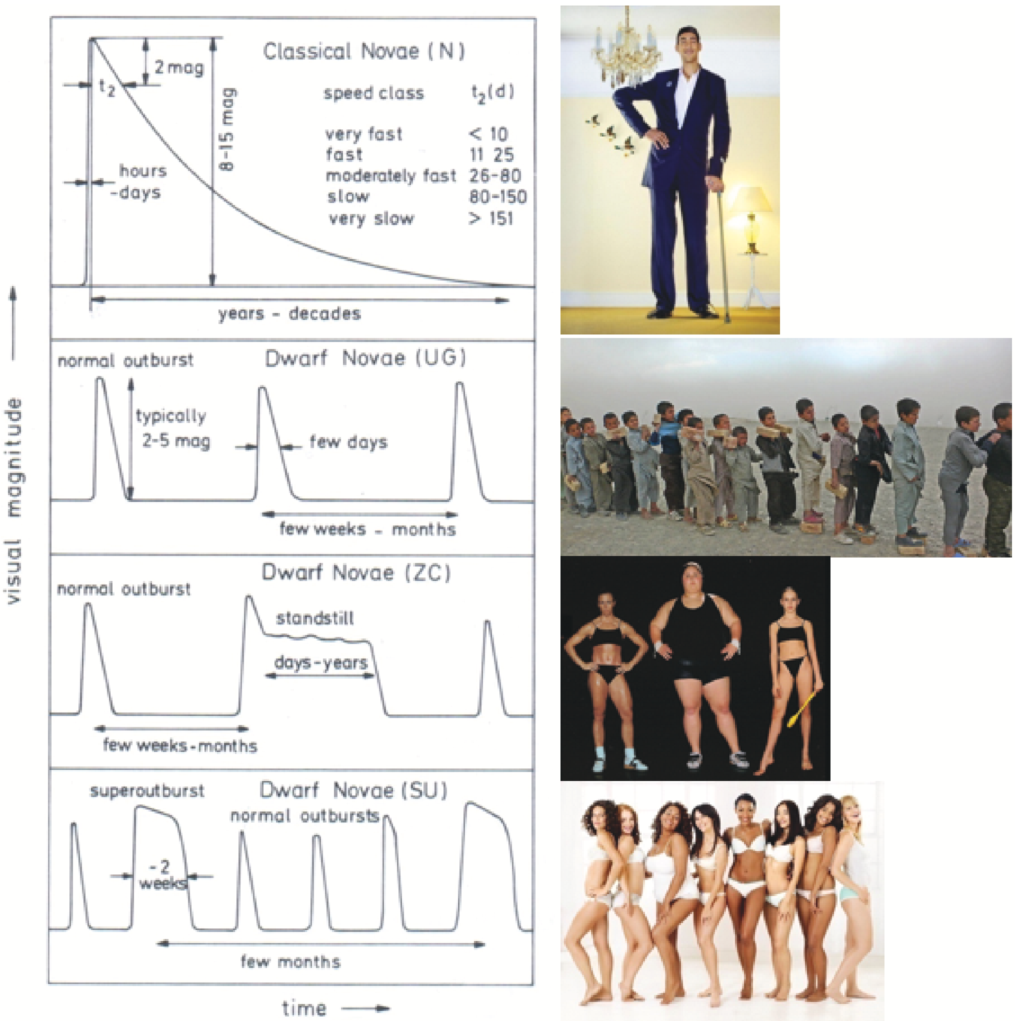


Figure 5: Left: visual light curves of classical novae (top panel) and of dwarf novae of the U Gem, Z Cam, and SU UMa types (lower three panels) (Ritter, 1992). Right: different groups of people that are all "humans".

Indeed, if we consider the main characteristics of different kind of CVs (fig. 5): Left - visual light curves of classical novae (top panel) and of dwarf novae of the U Gem, Z Cam, and SU UMa types (lower three panels) (Ritter, 1992) and we associate to each of these groups of people which roughly resemble the light curves (right), it appears evident that all these people are "humans" as all the "CVs" are "CVs".

This intuitive but ingenious result was obtained scientifically many years ago by Lipunov (1987) and Lipunov & Postnov (1988). They realized a general model for compact accreting stars: **The Scenario Machine**.

Starting from the trivial definition of X-Ray Binaries (XRBs): they are binary systems emitting X-rays, a natural question arises. Are these systems governed by few physical parameters independent of their nature? The answer is positive. Indeed, high mass XRBs (HMXRBs), low mass XRBs (LMXRBs), anomalous X-ray pulsars (AXPs), and CVs can be considered as gravimagnetic rotators: a body with mass M, having a magnetic moment $\vec{\mu}$, rotating with rotational velocity $\vec{\omega}$, being the two axis not necessarily coincident, as sketched in Fig. 6. Introducing a physical parameter, $y = \dot{M}/\mu^2$, named *gravimagnetic parameter*, all the gravimagnetic rotators are contained in a plane Log P_{spin} vs Log y.

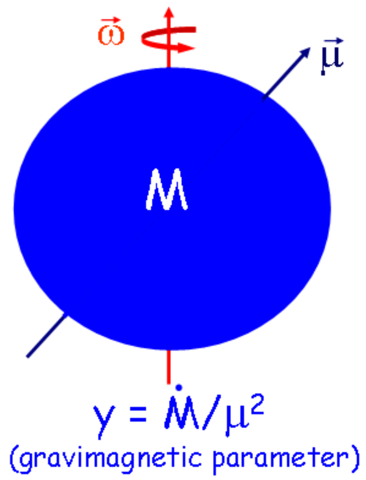


Figure 6: Gravimagnetic rotator: a body with mass M, having a magnetic moment $\vec{\mu}$, rotating with rotational velocity $\vec{\omega}$. The parameter $y = \dot{M}/\mu^2$ is called *gravimagnetic parameter* (Lipunov, 1987; Lipunov & Postnov, 1988).

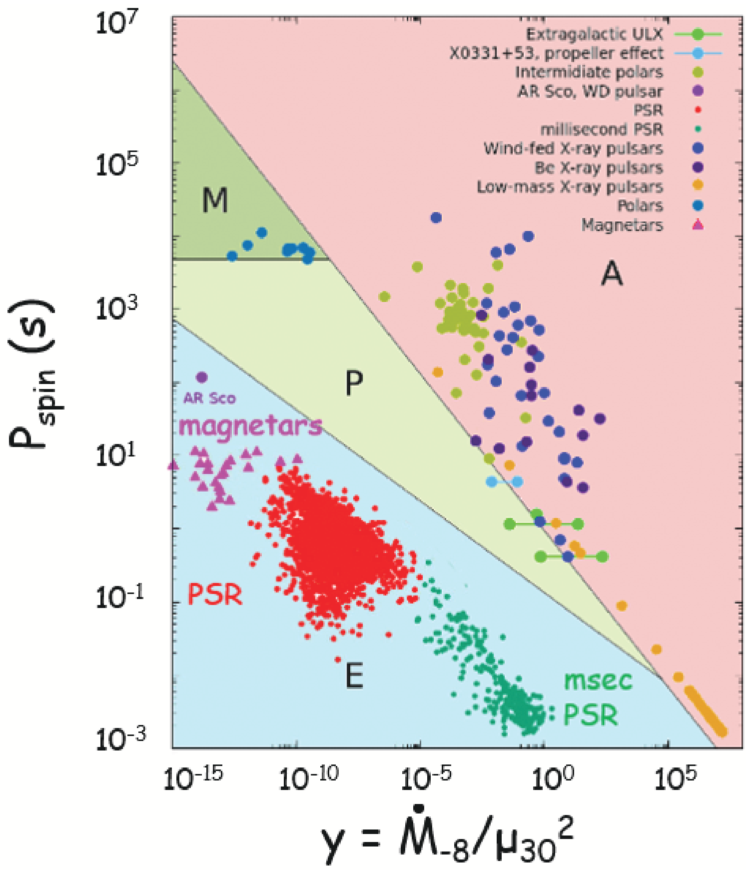
The *Scenario Machine* (Monte Carlo simulations of binary evolution) permits to build up the complete picture of all possible evolutionary stages of binaries in the Galaxy. The basic evolution equation (1) used for 500,000 systems containing magnetized stars provided the results contained in the plane Log P_{spin}–Log y, reported in the upper panel of Fig. 7. The spin period P_{spin} is expressed in seconds and the gravimagnetic parameter is expressed in unit of 10^{-42} g s^{-1} G^{-2} cm^{-6}. The symbols used for the different types of binaries are explained in the lower panel of Fig. 7. The definition of the characteristic radii can be found in the paper by Lipunov (1987).

Observational examples of various types of rotators are reported in Fig. 8 (Lipunov, 1987).

$$\frac{dI\omega}{dt} = \dot{M}K_{su} - \frac{\kappa_t \mu^2}{R_t^3} \quad (1)$$

where:

K_{su} = specific angular momentum applied by the accretion matter to the rotator;
$K_{su} = \sqrt{GM_x R_d}$ for Keplerian disk accretion;
$K_{su} = \eta_t \Omega R_g^2$ for wind accretion in a binary;
$K_{su} \sim 0$ for a single magnetic rotator;
R_d = radius of the inner disk edge;
Ω = rotational frequency of the binary system;
$\eta_t = 1/4$ (Illarionov & Sunyaev, 1975);
κ_t = dimensionless factor;
R_t = characteristic radius;



The rotator classification

Designation	Name	Physical sense	
E	Ejector	$R_{st} > \max\{R_G, R_l\}$	
P	Propeller	$R_c < R_{st} \le \max\{R_G, R_l\}$	
A	Accretor	$R_{st} \le R_G$ and $R_{st} \le R_c$	$\dot{M}_c \le \dot{M}_{cr}$
G	Georotator	$R_G < R_{st} \le R_c$	
M	Magnetor	$R_{st} > a$ and $R_c > a$	
SE	Superejector	$R_{st} > R_l$	
SP	Superpropeller	$R_c < R_{st} \le R_l$	$\dot{M}_c > \dot{M}_{cr}$
SA	Superaccretor	$R_{st} \le R_c$ and $R_{st} \le R_G$	

Figure 7: Upper panel: distribution of magnetic rotators in the plane "Spin Period" – "Gavimagnetic Parameter" (adopted from Lipunov, Grinshpun & Vlasenko, 2021); lower panel: classification of rotators (Lipunov, 1987).

$\dot{M}$ = accretion rate in different regimes.

Using the "Scenario Machine" Raguzova & Lipunov (1999) obtained an evolutionary track that can lead to the formation of Be/BH systems. The modern evolutionary scenario predicts the existence of binary black holes on eccentric orbits around Be stars and such systems may be discovered in the near future... Like happened!

Indeed, Raguzova & Lipunov (1999) calculations show that binary black holes with Be stars

Type of rotator	Designation	The clearly confirmed observational example	Model assumptions
Ejector	E	Radiopulsars	LSI + 61°303, Cyg X-3, BL Lac objects,
Propeller	P	–	Transient X-ray sources, γ-bursts, some cataclysmic variables (dwarf novae), magnetic Ap-stars
Accretor	A	X-ray pulsars, X-ray bursters, cataclysmic variables with white dwarfs, novae, intermediate polars	–
Superejector	SE	–	SS 433, AGN, QSO
Superpropeller	SP	–	–
Superaccretor	SA	–	SS 433
Georotator	G	–	–
Magnetor	M	Polars	–

Figure 8: Observational examples of rotators (Lipunov, 1987).

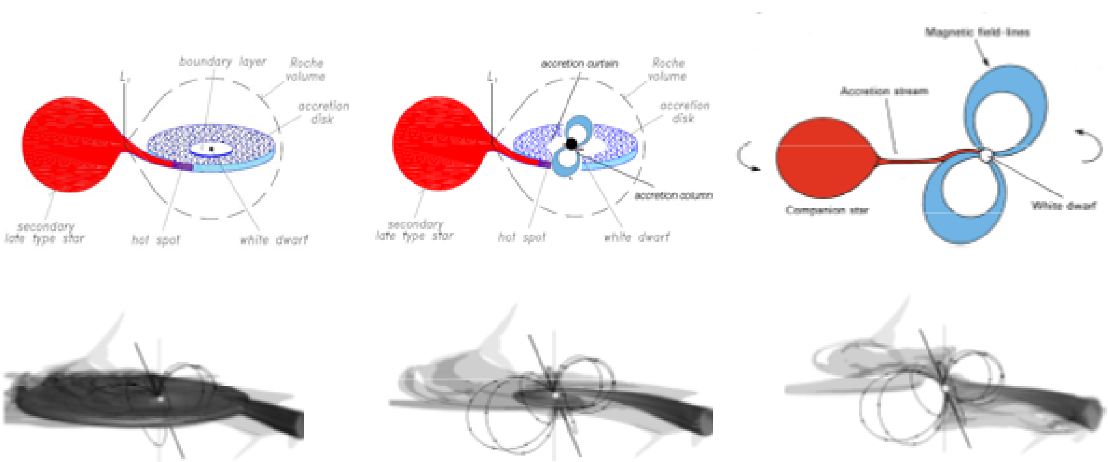


Figure 9: Upper panel: sketch of NMCVs, IPs and Ps (adopted from Giovannelli, 2017b); lower panel: 3D MHD simulations of NMCVs, IPs and Ps (adapted from Bisikalo & Zhilkin, 2015).

must have $0.2 < e < 0.8$. It is particularly difficult to detect such systems as most of their spectroscopic variations occur in a relatively small portion of the orbit, and could easily be missed if the systems are observed at widely separated epochs.

The CVs are usually classified into three classes depending on the magnetic field of the white dwarf: non-magnetic CVs (NMCVs), intermediate polar (IPs) and polar (Ps) with magnetic field intensities of $\lesssim 10^5$, $\approx 10^{5-6}$ and $\approx 10^{7-8}$ G, respectively. Figure 9 shows the three classes of CVs. In the upper panel a sketch (Giovannelli, 2017b), and in the lower panel the 3D MHD (Magneto Hydro-Dynamical) simulations (Bisikalo & Zhilkin, 2015).

Figure 10 shows the contribution of the various components (red star, accretion disc and boundary layer) of a NMCV from the infrared (IR) to extreme ultraviolet (EUV) frequencies (Pringle & Wade, 1985).

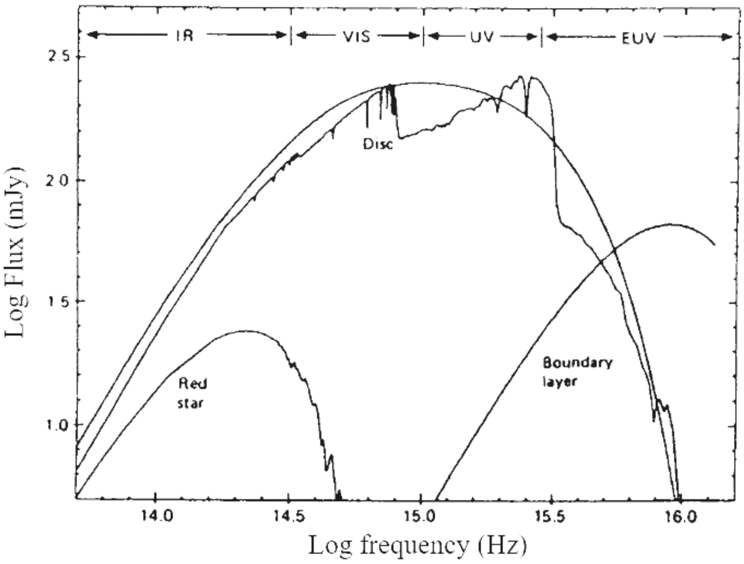


Figure 10: The flux emitted by a NMCV versus frequency (adopted from Pringle & Wade, 1985).

2. Cataclysmic variables as a single class

Following the indications coming from the "scenario machine" we can consider all the cataclysmic variables as a single class whose components are distinguished from each other by the orbital period, the spin period and the intensity of the magnetic field of the white dwarf.

Figure 11 shows the number of all CVs versus the orbital period (Armstrong, 2013). If someone prefers to look at the same graph as Fig. 11 with the subdivision between non-magnetic CVs (NMCVs), Polars (Ps) and intermediate Polars (IPs) he will obtain the graph in Fig. 12 (Ferrario, de Martino & Gänsicke, 2015).

The evolutionary path of the CVs is illustrated in Fig 13 (Rodriguez-Gil, 2003). 50% of the CVs are found in the area with orbital periods above 3 h, 39% below 2 h and in the band known as the "Period Gap" we find the 11% of CVs (Gänsicke, 2005). Most CVs lie either above or below the "Period Gap" region, and this observation can be explained by invoking two mechanisms for angular momentum (J) loss in CVs. The first is magnetic braking, a scenario in which material is driven from the CV in a wind via the magnetic field of the secondary. The second mechanism is gravitational wave radiation (GWR). In long-period CVs, magnetic braking is believed to dominate evolution. As the secondary evolves, its magnetic field weakens, and it is thought that magnetic braking essentially turns off for systems when $M_2 \sim 0.3\ M_\odot$ - which corresponds to a $P_{orb} \sim 3$ h. Meanwhile, GWR strengthens as P_{orb} shortens, and should dominate evolution for the shorter-period CVs. Within this picture, we can interpret the period gap as follows. As the secondary evolves below $0.3\ M_\odot$, the efficiency of magnetic braking decreases rapidly. Meanwhile, GWR is not yet sufficiently strong to keep the secondary in contact with its Roche lobe. Hence the secondary detaches from its Roche lobe, mass transfer ceases, and the binary becomes too faint to observe. The binary separation continues to shrink, however, due to the effect of GWR – which is strengthening. Once the system reaches the orbital period $P_{orb} \sim 2$ h, GWR losses are sufficient to re-establish

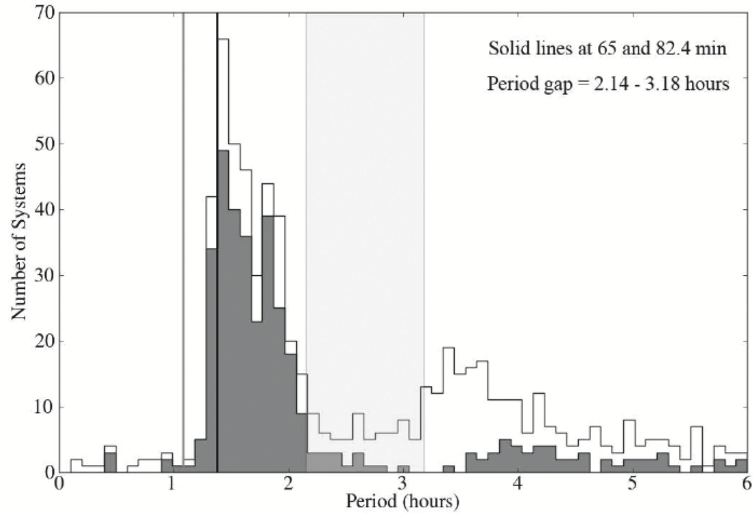


Figure 11: The distribution of CVs according to orbital period (Ritter & Kolb, version 7.14 (2010). The white region includes all non-magnetic CVs; the dark grey region represents CVs that experience dwarf nova explosions. The lightly-shaded rectangular area indicates the observed period gap between 2.14 – 3.18 hours. The light grey line represents the theoretical period minimum of 65 minutes (Kolb, 1993); the black line represents the observed period minimum of 82 minutes (Gänsicke et al., 2009) (adopted from Armstrong, 2013).

the secondary's connection to its Roche lobe. Mass transfer recommences and we see the system reappears at $P_{orb} \sim 2$ h (Armstrong, 2013 and the references therein).

In my opinion is extremely important to remark once more that there is continuity among the "different classes" of CVs. This is coming from the pathway of evolution of CVs that is driven by angular momentum (J) loss, which provokes a decrease of the orbital period P_{orb}. Thus, all long P_{orb} CVs cross SW Sex regime before entering in the "Period Gap". SW Sex phenomenon is an evolutionary stage in the life of CVs. So that in synthesis we can say that magnetic braking is mainly responsible of the J-loss for CVs with $P_{orb} \gtrsim 3$ h and GWR is mainly responsible of J-loss for CVs with $P_{orb} \lesssim 2$ h.

Further proof of the continuity in the evolution of the CVs is illustrated in Fig. 14 which reports the intensity of the magnetic field B versus the orbital period for the polars and intermediate polars. The excursion ranges for B and for the orbital periods of both the polars and the intermediate polars are shown with the black lines. In the light blue rectangle there are the polars, in the green rectangle there are the intermediate polars. In the midnight blue rectangle there are both polar and intermediate polars. The purple rectangle indicates the "Period Gap" (Giovannelli & Sabau-Graziati, 2015a).

3. Accretion processes in cosmic sources

Accretion is a universal phenomenon that takes place in the vast majority of astrophysical objects. The progress of ground-based and space-borne observational facilities has resulted in the great amount of information on various accreting astrophysical objects, collected within the last

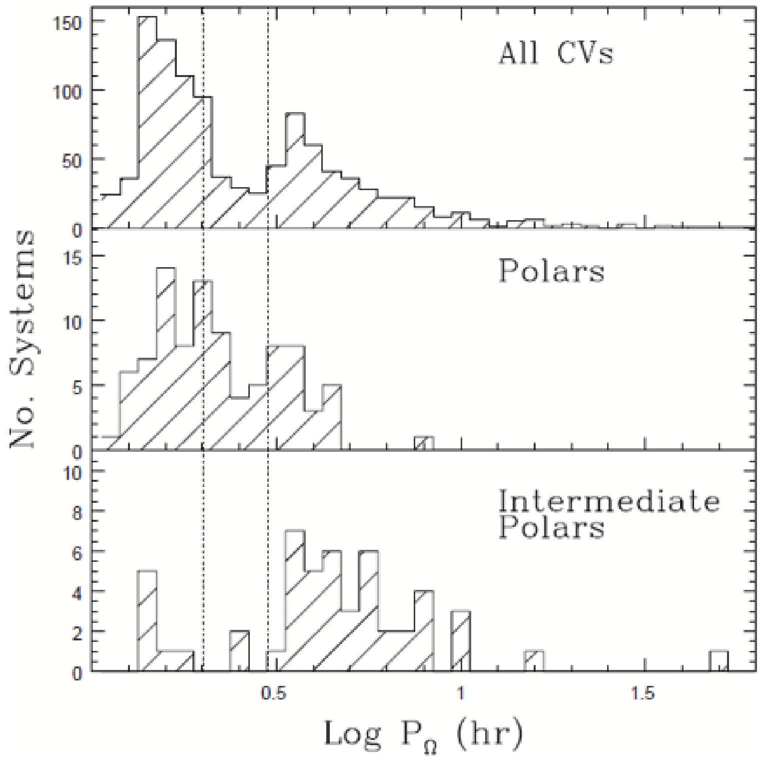


Figure 12: The orbital period distribution of CVs (top) and of the magnetic types Polars (middle) and IPs (bottom). The latest version (v7.20) of the Ritter and Kolb (2003) CV catalogue is used. A few identifications were corrected. The vertical lines mark the 2-3h orbital period gap (adopted from Ferrario, de Martino & Gänsicke, 2015).

decades. The accretion is accompanied by the process of extensive energy release that takes place on the surface of an accreting object and in various gaseous envelopes, accretion disk, jets and other elements of the flow pattern. The results of observations inspired the intensive development of accretion theory, which, in turn, enabled us to study unique properties of accreting objects and physical conditions in the surrounding environment. One of the most interesting outcomes of this intensive study is the fact that accretion processes are, in a sense, self-similar on various spatial scales from planetary systems to galaxies. This fact gives us new opportunities to investigate objects that, by various reasons, are not available for direct study.

Cataclysmic variable stars are unique natural laboratories where one can conduct the detailed observational study of accretion processes and accretion disks. Indeed, among the cosmic systems where accretion processes occur, undoubtedly, non-magnetic CVs, intermediate polars and polars constitute the most powerful probe to test our theories of the various modes of accretion. The reason is rather simple: CVs are enough close to us and their processes develop in time-scales relatively easy to be followed and enough energetic to be easily detected. The long term evolution of CV systems accreting at a prohibitive rate has become a hot topic both in terms of the fate of such systems (all sorts of supernovae) and the microphysics of Eddington and super Eddington mass accretion and mass loss flows. In particular we stress one of the hottest topics in present day

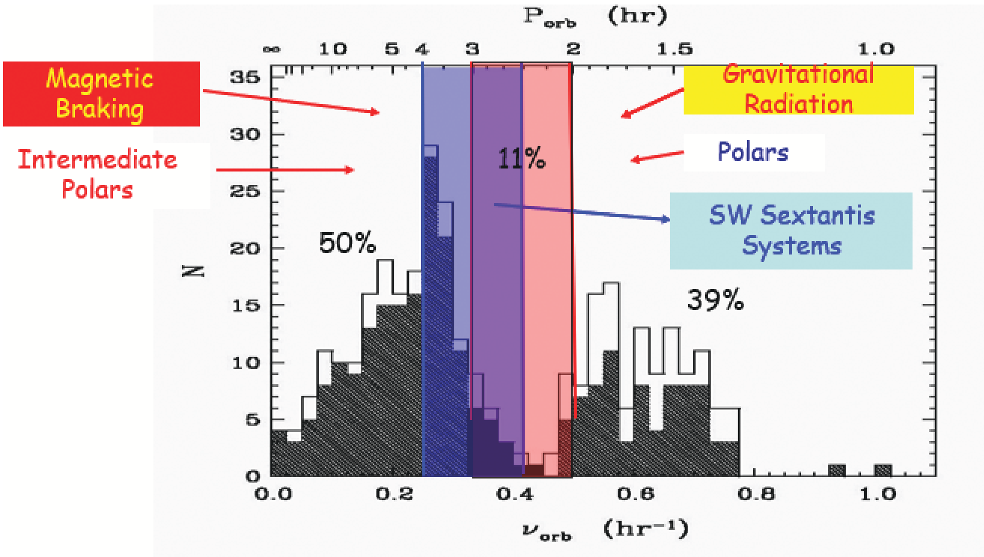


Figure 13: Number of CVs versus P_{orb}. All long P_{orb} CVs cross SW Sex regime before entering in the "Period Gap". SW Sex phenomenon is an evolutionary stage in the life of CVs. Light-blue rectangle shows the region where the SW Sex systems lie, and the light-red rectangle shows the "Period Gap". (after Rodriguez-Gil, 2003).

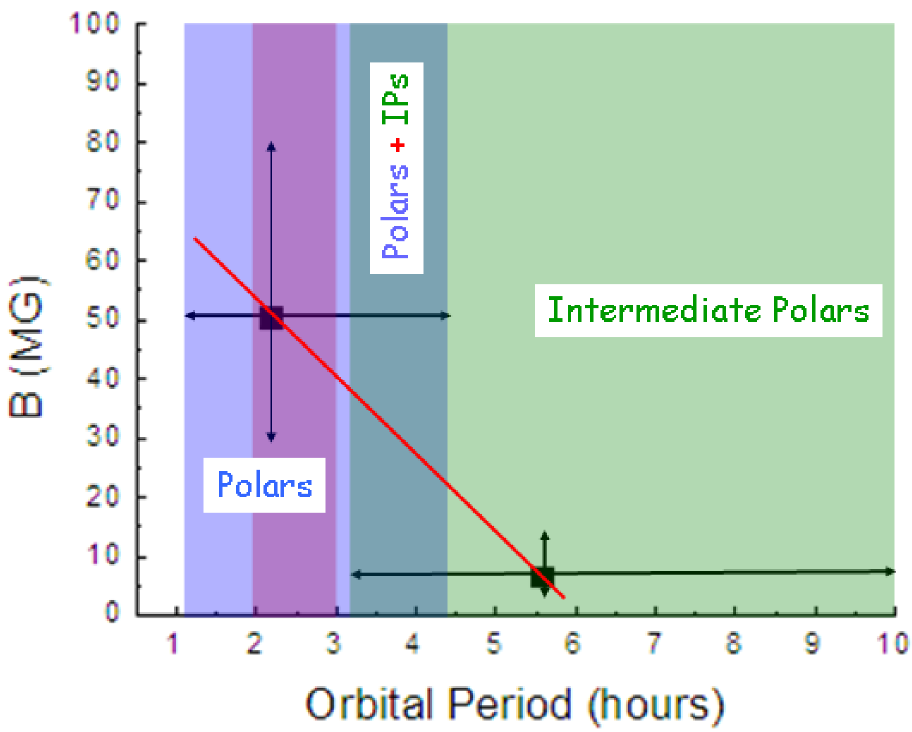


Figure 14: Magnetic field intensity B vs P_{orb} for polars and intermediate polars. In the light blue rectangle there are the polars, in the green rectangle there are the intermediate polars. In the midnight blue rectangle there are both polar and intermediate polars. The purple rectangle indicates the "Period Gap" (adopted from Giovannelli & Sabau-Graziati, 2015a).

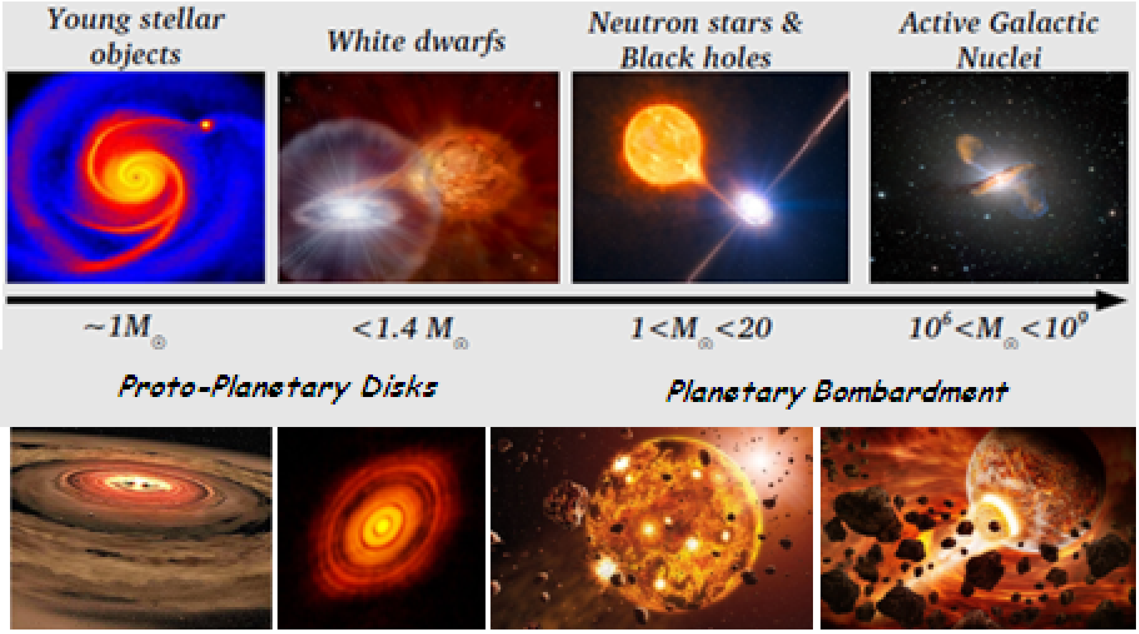


Figure 15: Accretion processes in different cosmic sources (adopted from Giovannelli & Sabau-Graziati, 2016, after Scaringi, 2015).

astrophysics, namely the progenitors of SN-Ia. This problem is connected with fundamental issues in cosmology. Novae and recurrent novae are the most promising progenitor candidates but so far could not be nailed down.

Figure 15 shows a sketch of cosmic systems where accretion processes occur (Giovannelli & Sabau-Graziati, 2016, after Scaringi, 2015).

Following the paper by Abramowicz & Straub (2014) accretion disks are flattened astronomical objects made of rapidly rotating gas which slowly spirals onto a central gravitating body. The gravitational energy of infalling matter extracted in accretion disks powers stellar binaries, active galactic nuclei, proto-planetary disks and some GRBs. In accretion disks the high angular momentum, J, of rotating matter is gradually transported outwards by stresses (related to turbulence, viscosity, shear and magnetic fields). This gradual loss of J allows matter to progressively move inwards, towards the centre of gravity. The gravitational energy of the gaseous matter is thereby converted to heat. A fraction of the heat is converted into radiation, which partially escapes and cools down the accretion disk. Accretion disk physics is thus governed by a non-linear combination of many processes, including gravity, hydrodynamics, viscosity, radiation and magnetic fields. The observable physical quantity of radiation produced in accretion disks is the luminosity. As photons carry momentum and thus can exert pressure there is a maximum possible luminosity at which gravity is able to balance the outward pressure of radiation.

The luminosity generated by a steady, spherically symmetric accretion flow cannot exceed notably the Eddington limit, defined as:

$$L_E = 4\pi G M m_p c/\sigma_T \simeq 1.2 \times 10^{38} (M/M_\odot)\ \mathrm{erg\,s^{-1}}\,, \tag{2}$$

where G is the gravitational constant, m_p the proton mass, σ_T the Thompson cross section, c the light velocity, M the mass of the central collapsed object and $M_\odot$ the solar mass.

The typical mass of a neutron star is 1.4 M⊙, thus $L_E \simeq 2{\times}10^{38}$ erg s^{-1}.

Since accretion disks are not spherical and often have additional stresses that can counteract the radiation pressure along with gravity, they may be brighter than this limit and radiate at super-Eddington luminosity.

If the isotropic luminosity of an accreting object could largely exceed the Eddington limit L_E, the pressure of the emerging radiation could prevail over the gravitational force attracting the accreting gas, with the consequence of stopping the accretion.

Reviews about *Accretion Processes in Cosmic Sources: theories vs experiments* have been published by Giovannelli & Sabau-Graziati (2016) and Giovannelli (2018) and the references therein. The accretion processes in cosmic sources has been also discussed in the review paper by Giovannelli (2024a).

3.1 Accretion onto white dwarfs

Accretion of matter onto WD can take place through a disk, a ring-like structure or an accretion stream depending on the WD magnetic field strength, the binary orbital period and mass accretion rate. The physical conditions of the material impinging onto the WD and emitting X-rays are still to be investigated. In non-magnetic CVs the WD magnetic field strength is low enough, $B_{WD} \leq 10^5$ G, to allow the formation of an accretion disk and X-rays are emitted at the disk Boundary Layer (BL). In highly magnetized CVs, $B_{WD} \geq 10^7$ G, material is directly accreted onto the WD poles flowing along the magnetic field lines. A partial accretion disk (a sort of ring) can be formed at intermediate field strengths ($10^5 \leq B_{WD} \leq 10^7$ G (see Fig. 9, where the 3D MHD simulations of the three cases are reported).

At the WD poles a stand-off shock is formed. The post-shock accretion column is thought to cool via bremstrahlung (hard X-rays), recombination processes and cyclotron radiation. The relative proportion of these cooling mechanisms strongly depends on the WD magnetic field (Fischer & Beuermann 2001). An interesting discussion about *Dissecting accretion and outflows in accreting white dwarf binaries* is reported by de Martino et al. (2015).

Therefore, the magnetic field intensity plays a fundamental role in the process of accretion of matter onto the compact star. Thus Lipunov's diagram (log P_{spin} vs log y) appears as the best way for localizing the position of MWDs, both polars and IPs, as shown in Fig. 7. In this figure, also the positions of other gravimagnetic rotators are shown.

The extraordinary discovery of the first white dwarf pulsar, AR Sco (P_{orb} = 3.57 h ; P_{spin} = 1.97 m; $0.81\ M_\odot < M_1 \leq 1.29 M_\odot$; $0.28\ M_\odot < M_2 \leq 0.45 M_\odot$) (Marsh et al., 2016), and the strong linear polarization (≤ 40%) variable with P_{orb} and P_{spin} and beat period detected by Buckley et al. (2017) suggested to Lipunov (2018) and to Lipunov, Grinshpun & Vlasenko (2021) to update Lipunov's diagram Log P_{spin} vs Log μ. Indeed, the pulsed luminosity of AR Sco is powered by the spin-down of the rapidly-rotating WD which is highly magnetised (≤ 500 MG). In the updated diagram of Fig. 7 the position of AR Sco is also reported. It lies just in the ejector zone together with the pulsars.

Sion (http://astronomy.villanova.edu/faculty/sion/CV/index.html) states that in the Galaxy we could expect ≈ 10^6 CVs. One of the big questions that arises is: "can all of the observed CVs and the phenomena associated with them be understood in terms of a single unified picture?" Other

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questions relate to the relative probabilities that CVs will be observed at particular stages in their evolution, and how the observations of CVs at the current epoch can be used to determine their ultimate fate.

To address these questions Nelson (2012) and Goliasch & Nelson (2015) have undertaken a massive computational effort to theoretically simulate the evolution of most of the possible CVs that could be produced by nature. The temporal evolution of 56,000 nascent CVs was followed over an age of 10 billion years using the MESA stellar evolution code. According to Nelson, "*This is the most ambitious analysis of the properties of an entire CV population that has ever been undertaken. The whole project required several core-years of CPU time*."

While many of the results confirmed what had already been inferred about the properties of CVs, there were a number of surprises including the identification of a number of previously unexplored evolutionary pathways. But, as expected, a sharp bifurcation was found between nascent CVs that evolved to produce double white-dwarf binaries (including ones containing helium and hybrid white dwarfs), and ones that continuously transferred mass over the lifetime of the universe. In addition, the predictions of the theoretical simulations were in good general agreement with the observations of CVs with reasonably well-measured properties.

What was surprising was the large number of short-period "ultracompact" binaries (AM CVn stars) that were produced and, especially, the enormous depletion of carbon relative to nitrogen and oxygen that is predicted at certain epochs for evolved systems. As Nelson points out, "*It seems that nature has provided us with a unique way to identify CVs that descended from a highly evolved state based on their carbon abundances. There is already some observational evidence to suggest that there is a significant depletion of carbon in certain CVs. This could be a really critical test that will allow us to infer the lineage of some CVs and predict what their fate will be*".

4. Classical and Recurrent Novae

Classical novae are expected to recur on timescales from 100,000 years to just a few decades. The most important physical parameters controlling this recurrence timescale are the WD mass, and the mass accretion rate from the secondary (e.g. Yaron et al. 2005). Once classical nova (CN) is recorded more than once, it can be designated as "recurrent" (RN). Since the WD and the binary system remain intact after an outburst, it is possible that classical novae may actually be the same as recurrent novae if observed over a long enough time period. While the interval between outbursts of recurrent novae range from 10 to 100 years, it has been estimated that the time interval for classical novae would range from about 30,000 years for a 1.3 $M_\odot$ WD to 100,000 years for a 0.6 $M_\odot$ WD. Given long enough - it is expected that all classical novae will be observed as recurrent novae.

The long term behaviour of classical old novae, and the optical behaviour of CNe in outburst were discussed by Bianchini (1990), and Seitter (1990), respectively. The books by Cassatella & Viotti (1990) and by Bode & Evans (2008) are very useful for studying the physics of classical novae.

Recurrent novae are a rare sub-class of CVs; WDs accreting material from a binary companion in which more than one classical nova-type outburst has been observed (see the book of Hellier, 2001 for a comprehensive review of CVs). Nova outbursts are suspected to be due to a thermonuclear runaway on the surface of the WD, which releases huge amounts of thermal energy once a critical pressure is reached at the base of the shell of accreted material.

One of the most interesting RNe is RS Ophiuchi (RS Oph). It is an amazingly prolific recurrent nova, with recorded outbursts in 1898, 1907, 1933, 1945, 1958, 1967, 1985 and 2006 (Schaefer 2010). The short time between outbursts (~ 20 yrs) suggests that RS Oph hosts a massive WD accreting material at a significantly high rate.

In the latter paper Schaefer discussed not only RS Oph, but also the photometric histories of all known galactic RNe.

Classical and recurrent nova outbursts have been discussed by Bode (2011a,b) and Evans (2011). The proceedings of a conference about RS Oph and recurrent phenomenon can be very useful for details (Evans et al., 2008). General properties of quiescent novae have been discussed by Warner (2002). The very useful book of Bode & Evans (2008) about classical novae examines thermonuclear processes, the evolution of nova systems, nova atmospheres and winds, the evolution of dust and molecules in novae, nova remnants, and observations of novae in other galaxies. It includes observations across the electromagnetic spectrum, from radio to gamma rays, and discusses some of the most important outstanding problems in classical nova research.

Todate, more than four hundreds Galactic novae are known, according to the catalogs (Duerbeck, 1987; Downes et al., 2005; Ritter & Kolb, 2003, 2015; Mukai, 2012). The Galactic nova rate has been reviewed by Shafter (2017), who proposed a rate of 50^{+31}_{23} yr^{1}.

Recently, Kawash et al. (2022) presented the first estimate of the Galactic nova rate based on optical transient surveys covering the entire sky. They found a rate of 26 ± 5 yr^{-1}, in complete agreement with the value, ~ 25 yr^{-1}, reported by Matteucci et al. (2003), following the considerations discussed by Romano et al. (1999).

Poggiani (2021) report also the nova rates for M 31, M33, LMC, SMC, and M 87. Figure 16 show the nova rates determinations for the Milky Way, M 31 and M 33, with the relative references.

The orbital period has been measured only for a small fraction of known novae. The distribution of measured periods is shown in Fig. 17, where novae with evolved secondary stars and periods above 10 hours have been excluded. The distribution of nova periods has a peak between 3 and 4 hours, above the "period gap" of cataclysmic variables. Novae show an high mass accretion rate onto the white dwarf (Poggiani, 2021).

Of the ~ 400 known Galactic classical novae, only 10 of them are recurrent. Eight of them harbour evolved secondary stars, contrary to classical novae that contain main sequence stars (Darnley et al., 2012). They propose a new nova classification based on the evolutionary state of the secondary star, contrary the current schemes based on the properties of outbursts. Such classification contains three groups of novae: i) Main Sequence Nova (MS–Nova); ii) Sub–Giant Nova (SG–Nova); and iii) Red Giant branch Nova (RG–Nova).

The ten known Galactic RNe are by far (with the exception of perhaps M31N2008-12a) the best studied. An extremely comprehensive compilation of their observational properties and history was published by Schaefer (2010). The Galactic RNe naturally separate into three distinct classes: the symbiotic RNe, the five (four confirmed; V 2487 Ophiuchi suspected) with red giant donors, often referred to as the RS Ophiuchi-class; the three with sub-giant donors, or the U Scorpii class; and the T Pyxidis-class, those with short CN-like orbital periods. Some of the properties of these novae are shown in Fig. 18 (Darnley, 2021).

Authors	Rate (yr^{-1})
Lundmark 1935	50
Allen 1954	100
Kopylov 1955	50
Sharov 1972	260
Liller and Mayer 1987	73±24
Della Valle 1988	15±5
Ciardullo et ai. 1990	11-46
van den Bergh 1981	16
Della Valle and Livio 1994	15-24
Hatano et al. 1997	41±20
Shafter 1997	35±11
Shafter 2002	36±13
Matteucci et al. 2003	25
Darnley et al. 2006	34^{+15}_{12}
Mroz et al. 2015	13.8±2.6
Shafter 2017	50^{+31}_{-23}

Table 1: Galactic nova rates

Authors	Rate (yr^{-1})
Hubble 1929	30
Arp 1956	26±4
Capaccioli et al. 1989	29±4
Shafter and Irby 2001	37^{+12}_{-8}
Darnley et al. 2006	65^{+16}_{-15}

Table 2: M31 nova rates

Authors	Rate (yr^{-1})
Sharov 1993	<0.4
Della Valle et al.1994	4.7±1.5
Williams and Shafter 2004	$2.5^{+1.0}_{-0.7}$

Table 3: M33 nova rates

Figure 16: The Nova Rates in the Milky Way, M 31, and M 33 (adapted from Poggiani, 2021).

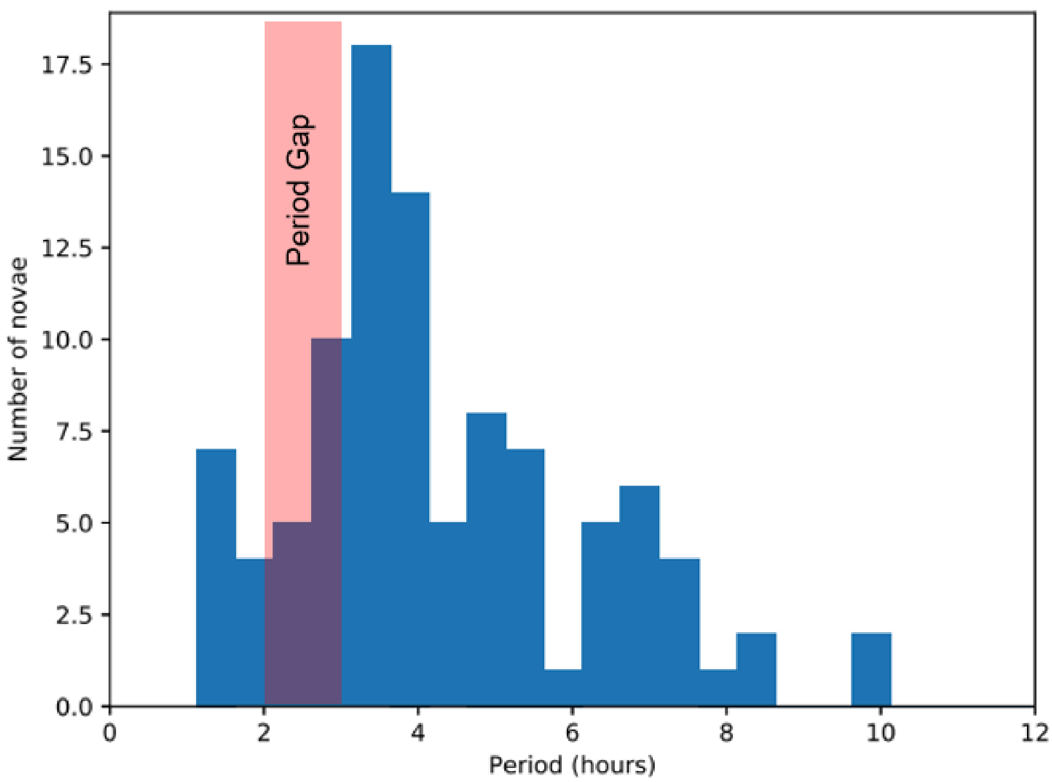

Figure 17: Distribution of the orbital periods of Galactic novae (Adapted from Poggiani, 2021).

Name	Known eruptions[a]	P_{rec} [years][b]	P_{orb} [days]	Next eruption[c]
	The RS Oph-class			
T Coronae Borealis	1866, 1946	~ 80	227.57	~ 2022
RS Ophiuchi	1898, 1907*, 1933, 1945*, 1958, 1967, 1985, 2006	15 ± 6	455.72	up to 2027
V2487 Ophiuchi[d]	1900, 1998	~ 98	...	~ 2096
V3890 Sagittarii	1962, 1990, 2019	29 ± 1	519.7 ± 0.3	2048 ± 1
V745 Scorpii	1937, ($\sim$1963), 1989, 2014	26 ± 1	510 ± 20	2040 ± 1
	The U Sco-class			
CI Aquillae	1917, 1941, ($\sim$1968), 2000	27 ± 4	0.62	2027 ± 4
V394 Coronae Australis	1949, 1987	~ 38	1.52	~ 2025
U Scorpii	1863, ($\sim$1873, $\sim$1884, $\sim$1894), 1906, 1917, ($\sim$1927), 1936, 1945, ($\sim$1955), 1969, 1979, 1987, 1999, 2010	10 ± 1	1.23	up to 2021
	The short orbital period systems			
IM Normae	1920, 2002	~ 82	0.10	~ 2084
T Pyxidis	1890, 1902, 1920, 1944, 1967, 2011	24 ± 12	0.08	2035 ± 12

Figure 18: Selected properties of the ten known Galactic recurrent novae (Adopted from Darnley, 2021).

An important not yet resolved problem is connected with the evolution and fate of Classical Novae. Patterson (2014) discussed this crucial problem. Classical novae rise from obscurity to shine among the brightest stars in the Galaxy. The story of how they return to quiescence is still only dimly known. Vast amounts of energy are loosed upon the WD and its companion, and the light curves of post-novae suggest that they take not a few years, but a few thousand years, to return to quiescence. In the meantime, the secondary may experience a lot of heating from the WD's radiation - enough to overwhelm its intrinsic nuclear luminosity. For this purpose he mentioned the case of BK Lyncis – the oldest old nova and a bell-wether for CVs evolution (Patterson et al., 2013). They discussed stellar physics behind this suggestion and proposed how it might be tested by time-series photometry in the months and years (and if possible, centuries) after outburst.

RNe play an important role in the studies of SN Ia progenitors (Surina, Bode & Darnley, 2015). RNe are likely progenitors of Type–Ia supernovae.

On the contrary, Shafter et al. (2015) estimated that $\sim 4\%$ of the nova eruptions seen in M31 over the past century are associated with RNe. A Monte Carlo analysis shows that the discovery efficiency for RNe may be as low as 10% that for novae in general, suggesting that as many as one in three nova eruptions observed in M31 arise from progenitor systems having recurrence times $\lesssim$ 100 yr. For plausible system parameters, it appears unlikely that RNe can provide a significant channel for the production of Type–Ia supernovae.

Important works have been developed about extragalactic nova populations (Shafter et al., 2014). Nova rates have been measured for more than a dozen galaxies spanning a wide range of Hubble types. They found that the recurrent nova population in the LMC appears to be higher than that seen in M31 and the Galaxy.

In order to brave this important problem the use of archival data is the only way to answer the big question. Now, huge and comprehensive set of archival RN data go back to 1890.

Excellent work about the archival data has been promoted by René Hudec, who scanned thousands plates belong to numerous astronomical observatories spread in the whole world (e.g. Hudec, R. & Hudec, L., 2013). Indeed, the astronomical plate archives represent the only method how to study the behavior of the CVs (and other astrophysical objects in general) over very long (100 years or even more) time intervals, and the only method to go back in time. In addition, huge monitoring times (up to 30,000 hrs of continuous monitoring) are available allowing to detect and to study rare events such as outbursts. The databases allow to study prominent spectra and/or spectral changes as well (Hudec, R. Hudec, L. & Klíma, M., 2012).

Starrfield, Iliadis & Hix (2016) in their review about *The Thermonuclear Runaway and the Classical Nova Outburst* described both the recent advances in our understanding of the progress of the outburst and outline some of the puzzles that are still outstanding. They reported on the effects of improving both the nuclear reaction rate library and including a modern nuclear reaction network in their one-dimensional, fully implicit, hydrodynamic computer code. In addition, there has been progress in observational studies of SNe Ia with implications about the progenitors, and they discussed that in their review.

Reviews about galactic and extragalactic novae has been published by Poggiani (2017a, 2021), in which she discusses the multifrequency observations that are contributing to understanding the process of explosions and of the long term evolution. She discusses the observations of novae over the electromagnetic spectrum, focusing on the morphology of the decline light curves, the spectroscopic investigations, the long term evolution, the recurrent novae, the gamma ray emission in novae, extragalactic novae, and the gravitational emission of novae.

In my opinion it is important to point out that even the Classical Novae and the Recurrent Novae do not belong to two classes of separate objects, but show continuity as always happens in nature; topic that we have already discussed in the introduction. Figure 19 shows such a continuity (Pagnotta & Schaefer, 2014; Pagnotta, 2015b).

Left panel of Fig. 19 (first published by Duerbeck, 1987) plots the amplitude of the nova eruption against the time (in days) to decline by 3 mag from peak, t_3; in this plot, the errors are smaller than the symbol size unless otherwise visible. All novae peak at approximately the same absolute magnitude, but RNe have higher average accretion rates and therefore brighter average quiescent magnitudes. This leads to small eruption amplitudes. Additionally, because of the smaller trigger masses required for RNe, the eruptions are shorter and faster than in CNe, so the t_3 values are smaller. The RNe (dark blue diamonds) are therefore clustered in the bottom left corner of this plot, with low amplitudes and low t_3 values. T Pyx and IM Nor are the notable exceptions, found mixed in with the CNe (brown circles) above the threshold, which is not surprising since they are unusual systems. To quantify the region that Duerbeck (1987) described as “void of classical novae,” Pagnotta & Schaefer (2014) define a threshold line of $A_0 = 14.5 - 4.5\times\log t_3$, which is drawn on the plot. 77.8% of the considered RNe have A - A_0 values < 0, while only three CN systems (2.3% of their sample) do. Those three systems (LS And, DE Cir, and V1187 Sco) are marked on the figure above. Another six systems (V868 Cen, CP Cru, V4361 Sgr, V697 Sco, V723 Sco, and V477 Sct) have A - A_0 < 1, marking them as interesting. V2487 Oph is plotted as a green square to keep it separate from both the RNe and the CNe.

Right panel of Fig. 19 shows the distribution of the expansion velocity of nova eruptions, as measured by the FWHM of the H_α line in km s^{-1} as close to peak as possible; the bin value labels along the x-axis are the (inclusive) maximum FWHM for that bin, so the first bin contains all systems with 0 km s^{-1} ≤ FWHM ≤ 1000 km s^{-1}, the second bin contains all systems with 1000 km s^{-1} < FWHM ≤ 2000 km s^{-1}, and so forth. The CNe (brown diagonal hashed region) have on average

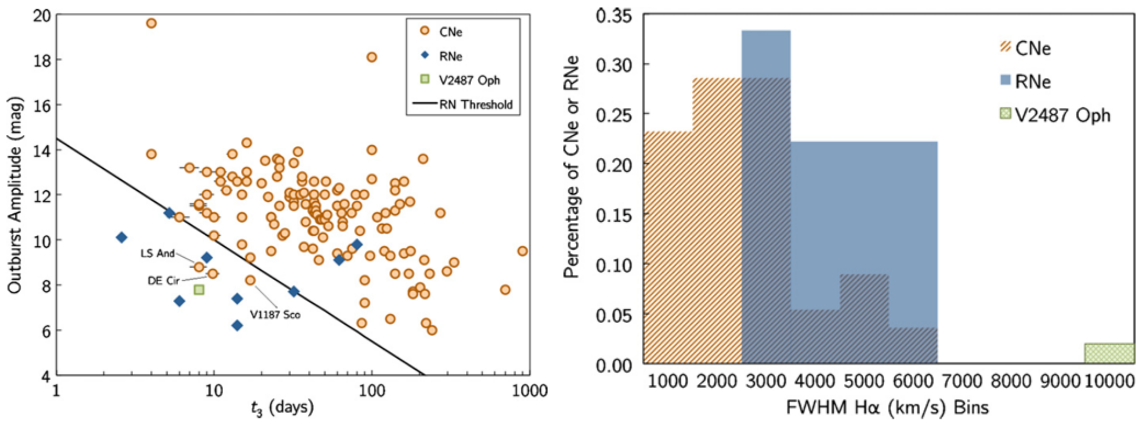

Figure 19: Left panel: Outburst Amplitude versus t_3. Right panel: Percentage of Classical Novae or Recurrent Novae versus FWHM H_α Bins (Adopted from Pagnotta & Schaefer, 2014).

much lower expansion velocities, due to their less massive WDs. The RNe (light blue solid region) have much higher expansion velocities because of the presence of a high-mass WD in the system. The populations are not completely distinct, as can be seen by the overlap in the distributions in this plot. Part of this is due to the natural continuum of nova eruption characteristics, and part is due to the fact that there are many RNe miscategorized as CNe. Pagnotta & Schaefer (2014) consider any CN with FWHM H_α > 2000 km s^{-1} to be a possible RN, and any CN with FWHM H_α > 3500 km s^{-1} to have a high probability of being recurrent. As it has been throughout the paper by Pagnotta & Schaefer (2014), V2487 Oph is treated separately from both the RN and CN samples; to that effect, it is depicted with green cross-hatching on the plot, at its observed expansion velocity of 10000 km s^{-1}, at the percentage amount it would be if it were grouped in with the CNe, which is a somewhat arbitrary y-value, chosen mostly to give a low height to that section of the histogram to depict the fact that there is only one object in their time-limited sample out there. They decided to keep V2487 Oph separate.

The Galactic RN fraction, the percentage of currently labeled CNe that are actually RNe, is FRN = 25% ± 10%. With this, we expect that roughly 100 (or between 60 and 140) of the 394 systems labeled as CNe are in fact currently active RNe for which only one eruption has been thus far discovered (Pagnotta & Schaefer, 2014).

Below I report an almost complete list of the reviews published in the literature on Classical Novae and Recurrent Novae which can facilitate the most demanding reader:

- Theory and observations of classical novae (Gallagher, J.S. & Starrfield, S., 1978);
- The nature of RNe (Ronald F. Webbink, Mario Livio & James W. Truran, Marina Orio, 1987);
- A review on classical novae outbursts (Starrfield, S. & Sparks, W.M., 1987);
- A Reference Catalogue and Atlas of Galactic Novae (Hilmar W. Duerbeck, 1987);
- Recent progress in understanding the eruptions of classical novae (Shara, M.M., 1989);

- Physics of Classical Novae (Angelo Cassatella & Roberto Viotti (Eds.), 1990);
- Classical novae and recurrent novae: General properties (Margherita Hack, Pierluigi Selvelli & Hilmar W. Duerbeck, 1993);
- The Recurrent Novae and Their Relation with Classical Novae (Anupama, G.C., 2002);
- Automated searches for extragalactic novae (Matthew J. Darnley, 2005);
- TOPICAL REVIEW: Nucleosynthesis in classical nova explosions (José, J & Hernanz, M., 2007);
- Extragalactic Novae (Allen W. Shafter, 2008);
- Classical Novae (Michael F. Bode & Aneurin Evans, Eds., 2008);
- Exhaustive review on all Galactic RNe (Schaefer, B.E., 2010);
- The outbursts of classical and recurrent novae (Bode, M.F., 2010);
- Classical and Recurrent Nova Outbursts (Bode, M.F., 2011b);
- Classical Novae (Michael F. Bode & Aneurin Evans, Eds., 2012);
- Classical and recurrent novae (Ulisse Munari, 2012);
- Unconventional observations of classical and recurrent novae (Elena Mason, 2012);
- Recurrent novae as progenitors of Type Ia supernovae (Mariko Kato & Izumi Hachisu, 2012);
- On the progenitors of galactic novae (Darnley, M.J. et al., 2012);
- Classical and Recurrent Nova Models (Jordi José et al., 2013);
- Investigation of the progenitors and outbursts of classical and recurrent novae (Farung Surina, 2014);
- Gamma-ray Emission from Nova Outbursts (Margarita Hernanz, 2014);
- Recurrent novae - a review (Mukai, K., 2015);
- Recurrent novae in M 31 (Shafter, A.W. et al., 2015);
- A New Review of Old Novae (Ashley Pagnotta, 2015a);
- Recurrent Novae: A Masquerade (Ashley Pagnotta, 2015b);
- Novae: a theoretical and observational study (Monika D. Soraisam, 2016);
- The galactic nova rate revisited (Shafter, A.W., 2017);
- Galactic and extragalactic novae - A Review (Rosa Poggiani, 2018);

- The Masses and Accretion Rates of White Dwarfs in Classical and Recurrent Novae (Michael M. Shara et al., 2018);
- Extragalactic Novae; A historical perspective (Shafter, Allen W., 2019);
- Review of light curves of novae in the modified scales. I. Recurrent novae (Rosenbush A., 2020);
- X-ray grating spectra of novae in outburst (Marina Orio, 2020);
- Counterparts of Far Eastern Guest Stars: Novae, supernovae, or something else? (Susanne M. Hoffmann & Nikolaus Vogt, 2020);
- Accrete, Accrete, Accrete...Bang! (and repeat): The Remarkable Recurrent Novae (Matthew J. Darnley, 2021);
- Classical Novae Masquerading as Dwarf Novae? Outburst Properties of Cataclysmic Variables with ASAS-SN (Kawash, A. et al., 2021);
- Galactic and Extragalactic Novae – A Multiwavelenght Review (Rosa Poggiani, 2021);
- Hydrodynamic Simulations of Classical Novae; CO and ONe White Dwarfs are Supernova Ia Progenitors (Starrfield, S. et al., 2021);
- New Insights into Classical Novae (Chomiuk, Metzger & Shen, 2021);
- Surveying the X-Ray Behavior of Novae as They Emit -Rays (Gordon et al., 2021);
- The Galactic Nova Rate: Estimates from the ASAS-SN and Gaia Surveys (Kawash et al., 2022);
- A Search for recurrent novae among Far Eastern guest stars (Susanne M. Hoffmann & Nikolaus Vogt, 2022);
- Association between Recurrent Novae and Nova Super-Remnants (Michael William Healy-Kalesh, 2024).

5. Progenitors of SN Ia

It is well accepted by the community that Type–Ia SNe are the result of the explosion of a carbon–oxygen WD that grows to near Chandrasekhar's limit in a close binary system (Hoyle & Fowler, 1960). But the debate is focussed around the different kinds of progenitors. Indeed, in the past, two families of progenitor models have been proposed. They differ in the mode of WD mass increase. The first family is the so–called *single degenerate* (SD) model (Whelan & Iben, 1973), in which the WD accretes and burns hydrogen–rich material from the companion. The second family is the so–called *double degenerate* (DD) model, in which the merging of two WDs in a close binary triggers the explosion (Webbing, 1984; Iben & Tutukov, 1984). The two scenarios produce different delay times for the birth of the binary system to explosion. Thus it is hopefully possible to discover the progenitors of Type–Ia SNe by studying their delay time distribution (DDT). The DDT can be determined empirically from the lag between the cosmic star formation rate and Type–Ia SN birthrate.

The energy released through runaway thermonuclear process ejects the majority of the unburnt hydrogen from the surface of the star in a shell of material moving at speeds of up to 1.5×10^3 km s^{-1}. This produces a bright but short-lived burst of light - the nova.

Although Type–Ia supernovae appear to have similar origin to classical novae, there are key differences. The most important is that in a classical nova, the thermonuclear runaway occurs only on the surface of the star, allowing the WD and the binary system to remain intact (e.g. Townsley & Bildsten, 2005). In a Type–Ia supernova, the thermonuclear runaway occurs within WD itself, completely disrupting the progenitor. This is reflected in the amount of energy released in the explosions, with classical novae releasing $\sim 10^{44}$ erg, and Type–Ia supernovae $\sim 10^{51}$ erg.

The possible progenitors of SN Ia are: i) Recurrent Novae; ii) Symbiotic stars; iii) Super-soft sources; iv) Double WD Binaries; and v) WDs accreting material from red–giant companions.

i) Recurrent Novae are just a subset of ordinary novae that happen to go off more than once per century.

As such, they are binary systems with matter flowing off a companion star onto a WD, accumulating on its surface until the pressure gets high enough to trigger a thermonuclear runaway that is the nova.

Only 10 RNe are known in our Milky Way galaxy, including: U Sco (1863, 1907, 1917, 1936, 1945, 1969, 1979, 1987, 1999); T Pyx (1890, 1902, 1920, 1944, 1967); T CrB (1866, 1946); RS Oph (1898, 1907, 1933, 1945, 1958, 1967, 1985, 2006).

To recur with $\tau_{rec} < 100$ years, RNe must have: high WD mass ($1.2M_\odot < M_{WD} < M_{Chandra}$) – being $M_{Chandra}$ the Chandrasekhar mass = 1.4 $M_\odot$ –, and high accretion rate ($\dot{M} \sim 10^{-7}$ $M_\odot$ yr^{-1}). SN Ia occurs if: i) the mass ejected for each eruption is less than the mass accreted onto the WD ($M_{ejected} < \dot{M}\ \tau_{rec}$); ii) the rate of death RNe must be enough to produce the SN Ia rate ($R_{RNdeath} = R_{SNIa}$), being $R_{RNdeath} = N_{RN} \times (0.2 M_\odot \dot{M})$.

In order to solve the problems we need to know τ_{rec} (recurrence time scale) from archive plates, N_{RN} (number of RNe in the Milky Way) from archive plates and AAVSO, $\dot{M}$ (mass accretion rate onto WD) from the average in the last century, $M_{ejected}$ (mass ejected in eruption) from pre–eruption eclipse timing.

Some results have been obtained for becoming optimists in solving the problem of SN Ia production. Indeed Schaefer (2011) obtained for CI Aql and U Sco $M_{ejected} << \dot{M}\ \tau_{rec}$.

Thus, WDs are gaining mass and the latter RNe will collapse as SN Ia. Moreover, for the Milky Way, M31, and LMC $R_{RNdeath} \sim N_{RN}$. Then there are enough RNe to supply the Type–Ia SN events.

ii) Symbiotic Stars contain WDs efficiently accreting material from the secondary star. In most cases they steadily burn H–rich material allowing them to grow in mass. Some of these systems can produce high mass WDs. In symbiotic RNe (SyRNe) the WD mass is already very close to Chandrasekhar's limit. For instance in V 407 Cyg a very massive WD is accreting material at a rate of $\sim 10^{-7}$ $M_\odot$ yr^{-1} from a Mira–type companion (Miszalski, Mikołajewska & Udalski, 2013).

iii) Super–soft Sources are probably WDs that accrete material and burn hydrogen. Voss & Nelemans (2008) discovered an object at the position of the Type–Ia SN2007on in the elliptical galaxy NGC1404 on pre–supernova archival X–ray images. This result favours the accretion model (SD) for this supernova, although the host galaxy is older than the age at which the explosions are predicted in SD models. However, the DD model cannot be ruled out by this event because a hot accretion disc is probably the intermediate configuration of the system, between first WD–WD Roche–lobe contact and explosion (Yoon, Podsiadlowski & Rosswog, 2007).

Greggio, Renzini & Daddi (2008) starting from the fact that Type–Ia SN events occur over an extended period of time, following a distribution of delay times (DDT), discussed theoretical DDT functions that accommodate both 'prompt' and 'tardy' SN events derived by empirically–based DDT functions. Moreover such theoretical DDT functions can account for all available observational constraints. The result is that SD/DD mix of SNIa's is predicted to vary in a systematic fashion as function of cosmic time (redshift).

iv) Double WDs Binaries are systems containing two WDs that can merge and giving rise to SN explosion. Yoon, Podsiadlowski & Rosswog (2007) explored the evolution of the merger of two carbon–oxygen (CO) WDs. Their results imply that at least some products of double CO WDs merger may be considered good candidates for the progenitors of Type–Ia SNe. Brown et al. (2011) and Kilic et al. (2011) studied a complete colour–selected sample of double–degenerate binary systems containing extremely low mass (ELM) ($\leq$ 0.25 $M_\odot$) WDs. Milky Way disc ELM WDs have a merger rate of $\approx 4 \times 10^{-5}$ yr^{-1} due to gravitational wave radiation. The ELM WD systems that undergo stable mass transfer can account for about 3% of AM CVn stars. The most important fact is that the ELM WD systems that may detonate merge at a rate comparable to the estimate rate of underluminous SNe. These SNe are rare explosions estimated to produce only $\sim$ 0.2 $M_\odot$ worth of ejecta. At least 25% of ELM WD sample belong to the old thick disc and halo components of our Galaxy. Thus, if merging ELM WD systems are the progenitors of under-luminous SNe, transient surveys must find them in both elliptical and spiral galaxies.

v) WDs accreting material from red–giant companions. Observations carried out by Patat et al. (2008) with VLT–UVES allowed to detect circumstellar material in a normal Type–Ia SN. The expansion velocities, densities and dimensions of the circumstellar envelope indicate that this material was ejected from the system prior to the explosion. The relatively low expansion velocities favour a progenitor system where a WD accretes material from a companion star, which is in the red–giant phase at the time of explosion.

Bianco et al. (2011) searched for a signature of a non–degenerate companion in three years of Supernova Legacy Survey data. They found that a contribution from WD/red–giant binary system to Type–Ia SN explosions greater than 10% at 2σ, and than 20% at 3σ level is ruled out.

Type–Ia SNe are used as primary distance indicators in cosmology (e.g. Phillips, 2005). Phillips (2012) reviewed the near–infrared (NIR) of Type–Ia SNe concluding that such SNe are essentially perfect standard candles in the NIR, displaying only a slight dependence of peak luminosity on decline rate and colour. Lira (1995) first noted that B–V evolution during the period from 30 to 90 days after V maximum is remarkably similar for all SN Ia events, regardless of light–curve shape. This fact was used by Phillips et al. (1999) to calibrate the dependence of the B_{max}–V_{max} and V_{max}–I_{max} colours on the light curve parameter Δm_{15} (B) which can, in turn, be used to separately evaluate the host galaxy extinction. Using these methods for eliminating the effect of the reddening, they reanalyzed the functional form of the decline rate versus luminosity relationship and gave a value of the Hubble constant of $H_0 = 63.3 \pm 2.2 \pm 3.3$ km s^{-1} Mpc^{-1}.

The use of Type–Ia SNe is also fundamental for determining some cosmological constraints, such as Ω_M and Ω_Λ that fit a ΛCDM models with values of 0.211 ± 0.034 (stat) ± 0.069 (sys) using a set of 252 high–redshift SNe (Guy et al., 2010) and $0.713^{+0.027}_{-0.029}$ (stat) $^{+0.036}_{-0.039}$ (sys) using a set of low–redshift nearby–Hubble–flow SNe (Kowalski et al., 2008), respectively.

In order to explore the difficult topic of the expansion of the Universe it is necessary to know the evolution of metallicity in old Universe that changes the Hubble Diagram shape. The proposed space observatory Super Nova Acceleration Probe (SNAP) is designed to measure the expansion of the Universe and to determine the nature of the mysterious Dark Energy that is accelerating this expansion (Aldering, 2005). SNAP is being proposed as part of the Joint Dark Energy Mission (JDEM) (Stril, Cahn & Linder, 2010), which is a cooperative venture between NASA and the U.S. Department of Energy. SNAP haS been superseded by WFIRST (Wide Field InfraRed Survey Telescope) (Gehrels et al., 2015).

WFIRST is a space telescope that will conduct unprecedented large surveys of the infrared universe to explore everything from our solar system to the edge of the observable universe, including planets throughout our galaxy and the nature of dark energy. The telescope was initially developed as the WFIRST0, and renamed in 2020 to honor Nancy Grace Roman, NASA's first Chief of Astronomy. Roman has been called the "mother" of NASA's Hubble Space Telescope. The Roman Space Telescope (RST) is currently planned for launch in the mid-2020s, and no later than 2027.

However, RST cannot achieve its main goal without progenitor/evolution solution.

The research about the progenitors of SN Ia is of course one of the most important problems, since it is strictly connected with the evolution of CVs. For instance, Maguire et al. (2012) present an analysis of the maximum light, near-ultraviolet (NUV; $2900 < \lambda < 5500$) spectra of 32 low-redshift ($0.001 < z < 0.08$) SNe Ia, obtained with the Hubble Space Telescope (HST) using the Space Telescope Imaging Spectrograph. They combine this spectroscopic sample with high-quality *gri* light curves obtained with robotic telescopes to measure SN Ia photometric parameters, such as stretch (light-curve width), optical colour and brightness. They confirm and strengthen earlier conclusions regarding the complex behaviour of SNe Ia in the NUV spectral region, but suggest that the correlations found are more useful in putting tighter constraints on the progenitor systems of SNe Ia and how their progenitor channels may vary with host galaxy properties (e.g. metallicity: Kistler et al., 2013) rather than improving the use of SNe Ia as cosmological probes.

Darnley et al. (2014) discussed on the galactic nova progenitor population. They presented a selection of the work and rationale that led to the proposal of a new nova classification scheme based not on the outburst properties but on the nature of the quiescent system. They also outlined the results of a photometric survey of a sample of quiescent Galactic novae, showing that the evolutionary state of the secondary can be easily determined and leading to a number of predictions, including their relevance to extragalactic work and the proposed link to type–Ia SNe.

In order to solve the problem of determining the SN Ia progenitors, it is also important to look at the RNe that show many similarities to CNe, but have had more than one recorded outburst. RNe play an important role as one of the suspected progenitor systems of Type–Ia SNe, which are used as primary distance indicators in cosmology. Thus, it is important to investigate the nature of their central binary systems to determine the relation between the parameters of the central system and the outburst type, and finally ascertain the population of novae that might be available to give rise to the progenitors of Type–Ia SNe. Surina, Bode & Darnley (2015) adopted a low outburst amplitude as a criterion that may help distinguish RNe from CNe and was therefore used to select targets for observations from ground-based observatories including the Liverpool Telescope and the Southern African Large Telescope as well as the full-sky space-based archive of the Solar Mass Ejection Imager (SMEI). They found that at least four objects currently classified as CNe are possibly RNe candidates based on their quiescent spectra. They also searched the SMEI archive for additional outbursts of bright CNe that might otherwise have been missed but did not find a conclusive example.

Another possible channel for triggering the explosion of SN Ia is that discussed by Chiosi et al. (2015). They explore the possibility that isolated CO–WDs with mass smaller than the Chandrasekhar limit may undergo nuclear runaway and SN explosion. If this channel could be confirmed it should be possible (i) to explain the star formation rate dependence of the SN Ia rate (e.g. Mannucci, Della Valle & Panagia, 2006); (ii) to provide some clues to interpreting the observational data on the ejected mass distribution of type–Ia SNe showing a significant rate of non-Chandrasekhar-mass progenitors of mass as low as 0.8 $M_\odot$ (Scalzo, Ruiter & Sim, 2014); and (iii) to account for the SNe exploding inside Planetary Nebulae in alternative to the core-degenerate scenario in which a WD merges with the hot core of an AGB star on a time interval $\leq 10^8$ yr since the WD formation (see Tsebrenko & Soker, 2015, for more details). With the models of Chiosi et al. (2015), a single CO–WD may reach the explosion stage soon after the formation if sufficiently massive ($> 1.0\ M_\odot$) and sufficiently rich in residual hydrogen ($X_H \simeq 10^{-19} - 10^{-20}$). The expected time delay after formation can be as low as about a few ten of thousand years.

Williams et al. (2014, 2016) report the results of a survey of M31 novae in quiescence. The derived catalog contains data for 38 spectroscopically confirmed novae from 2006 to 2012. They used Liverpool Telescope images of each nova during eruption to define an accurate position for each system. These positions were then matched to archival Hubble Space Telescope (HST) images and they performed photometry on any resolved objects that were coincident with the eruption positions. This in order to facilitate a search for their progenitor systems within archival Hubble Space Telescope (HST) data, with the aim of detecting systems with red giant secondaries (Red Giant-novae: RG-novae) or luminous accretion disks. They found an elevated proportion of nova systems with evolved secondaries that may imply the presence of a much larger population of recurrent novae than previously thought. This would have considerable impact, particularly with regards to their potential as Type–Ia SN progenitors. Their results also imply that RG-novae in M31 are more likely to be associated with the M31 disk population than the bulge, indeed the results are consistent with all RG-novae residing in the disk. If this result is confirmed in other galaxies, it suggests any Type–Ia SNe that originate from RG-nova systems are more likely to be associated with younger populations, and may be rare in old stellar populations, such as early-type galaxies.

An important paper by Churazov et al. (2014) reports the first ever detection of ^{56}Co lines at 847 and 1237 keV and a continuum in the 200-400 keV band from the Type–Ia SN2014J in M82 with INTEGRAL observatory. The data were taken between 50th and 100th day since the SN2014J outburst. The line fluxes suggest that $0.62 \pm 0.13\ M_\odot$ of radioactive ^{56}Ni were synthesized during the explosion. Line broadening gives a characteristic ejecta expansion velocity $V_e \sim 2100 \pm 500$ km s^{-1}. The flux at lower energies (200-400 keV) is consistent with the three-photon positronium annihilation, Compton downscattering and absorption in the $\sim 1.4\ M_\odot$ ejecta composed from equal fractions of iron-group and intermediate-mass elements and a kinetic energy $E_k \sim 1.4 \times 10^{51}$ erg. All these parameters are in broad agreement with a "canonical" model of an explosion of a Chandrasekhar-mass WD, providing an unambiguous proof of the nature of Type–Ia SNe as a thermonuclear explosion of a solar mass compact object. Late optical spectra (day 136 after the explosion) show rather symmetric Co and Fe line profiles, suggesting that, unless the viewing angle is special, the distribution of radioactive elements is symmetric in the ejecta (Churazov et al., 2015).

For comments and prospects about Type–Ia SN science in the decade 2010–2020 see the paper by Howell et al. (2009).

A recent review about type-Ia SN has been published by Liu, Röpke & Han (2023). They affirm that SNe Ia play a key role in the fields of astrophysics and cosmology. It is widely accepted that SNe Ia arise from thermonuclear explosions of white dwarfs (WDs) in binary systems. However, there is no consensus on the fundamental aspects of the nature of SN Ia progenitors and their actual explosion mechanism. This fundamentally flaws our understanding of these important astrophysical objects. They outline the diversity of SNe Ia and the proposed progenitor models and explosion mechanisms. They discuss the recent theoretical and observational progress in addressing the SN Ia progenitor and explosion mechanism in terms of the observables at various stages of the explosion, including rates and delay times, pre-explosion companion stars, ejecta–companion interaction, early excess emission, early radio/X-ray emission from circumstellar material interaction, surviving companion stars, late-time spectra and photometry, polarization signals, and supernova remnant properties, etc. Despite the efforts from both the theoretical and observational side, the questions of how the WDs reach an explosive state and what progenitor systems are more likely to produce SNe Ia remain open.

Below I report an almost complete list of the reviews published in the literature on type Ia SNe and their progenitors which can facilitate the most demanding reader:

- Supernovae and Supernova Remnants (Richard McCray & ZhenRu Wang (Eds.), 1996);
- Type Ia Supernovae and the Hubble Constant (David Branch, 1998);
- Type Ia Supernovae (B. Leibundgut, 2000);
- The observations of Type Ia supernovae (N.B. Suntzeff, 2000);
- Type Ia Supernova Explosion Models (Wolfgang Hillebrandt & Jens C. Niemeyer, 2000);
- Type Ia Supernovae: Theory and Cosmology (J.C. Niemeyer, James W. Truran (Eds.) & Barry F. Madore (Series Editor), 2000);
- Spectroscopically Peculiar Type Ia Supernovae and Implications for Progenitors (David Branch, 2001);
- Cosmological Implications from Observations Type Ia Supernovae (Bruno Leibundgut, 2001);

- Production of intermediate-mass and heavy nuclei (Thielemann, Friedrich-Karl et al., 2007);
- Type Ia Supernovae (J.C. Niemeyer & J.W. Truran (Eds.), 2010);
- Type Ia supernovae as stellar endpoints and cosmological tools (D. Andrew Howell, 2011);
- Gravitational Wave Emission from the Single-Degenerate Channel of Type Ia Supernovae (David Falta, Robert Fisher & Gaurav Khanna, 2011);
- Circumstellar Material in Type Ia Supernovae via Sodium Absorption Features (A. Sternberg et al., 2011);
- Type-Ia Supernova Rates and the Progenitor Problem: A Review (D. Maoz & F. Mannucci, 2012);
- The Usefulness of Type Ia Supernovae for Cosmology — a Personal Review (Kevin Krisciunas, 2012);
- Progenitors of type Ia supernovae (Bo Wang & Zhanwen Han, 2012);
- Observational Clues to the Progenitors of Type Ia Supernovae (Dan Maoz, Filippo Mannucci & Gijs Nelemans, 2014);
- A review of type Ia supernova spectra (Parrent, J., Friesen, B., Parthasarathy, M., 2014);
- Handbook of Supernovae (Athem W. Alsabti & Paul Murdin, 2017);
- Supernova Explosions (David Branch & J. Craig Wheeler, 2017);
- Type Ia supernovae with and without blueshifted narrow NaI D lines– how different is their structure? (S. Hachinger et al., 2017);
- Nucleosynthesis in Supernovae (Thielemann, Friedrich-Karl; Isern, Jordi; Perego, Albino; von Ballmoos, Peter, 2018);
- On the Progenitors of Type Ia Supernovae (Mario Livio & Paolo Mazzali, 2018);
- Type Ia Supernova Cosmology (Leibundgut, B. & Sullivan, M., 2018);
- Type Ia supernovae, standardizable candles, and gravity (Bill S. Wright & Baojiu Li, 2018);
- Dependence of Type Ia supernova luminosities on their local environment (Matthieu Roman et al., 2018);
- Red vs Blue: Early observations of thermonuclear supernovae reveal two distinct populations? (Maximilian D. Stritzinger et al., 2018);
- Meeting the Challenges of Modeling Astrophysical Thermonuclear Explosions: Castro, Maestro, and the AMReX Astrophysics Suite (Mike Zingale et al., 2018);
- Thermonuclear (Type Ia) Supernovae and Progenitor Evolution (Calder, A.C. et al., 2019);

- Type Ia Supernova Cosmology (B. Leibundgut & M. Sullivan, 2019);
- Nucleosynthesis in Supernovae (Thielemann, Friedrich-Karl; Isern, Jordi; Perego, Albino; von Ballmoos, Peter, 2019);
- Supernovae Ia in 2019 (review): A rising demand for spherical explosions (Noam Soker, 2019);
- Supernovae (Andrei Bykov, Chevalier Roger, John Raymond, Friedrich-Karl Thielemann, Maurizio Falanga and Rudolf von Steiger (Eds.), 2019);
- Type Ia Supernovae, The Standard Candle Hidden in the Brightest Explosions (Lewis Mackay, 2019);
- The progenitors of type-Ia supernovae in semidetached binaries with red giant donors (Dong-dong Liu et al., 2019);
- Strong dependence of Type Ia supernova standardization on the local specific star formation rate (M. Rigault et al., 2020);
- Rates and delay times of Type Ia supernovae in the Dark Energy Survey (P. Wiseman et al., 2021);
- A Brief Review of Historical Supernovae (Shawqi Al Dallal & Walid J. Azzam, 2021);
- A New Insight into the Observations and Analysis of Type Ia Supernovae (Qiuhe Peng & Jingjing Liu, 2021);
- Understanding Type Ia Supernova Diversity with PHOENIX (James M. Derkacy, 2022);
- Type Ia supernovae: Inside the universe's biggest blasts (Yvette Cendes, 2022);
- Prospects of Searching for Type Ia Supernovae with 2.5-m Wide Field Survey Telescope (Maokai Hu et al., 2022);
- Type Ia Supernova Explosions in Binary Systems: A Review (Zheng-Wei Liu, Friedrich K. Röpke, Zhanwen Han, 2023);
- Type Ia supernovae and their explosive nucleosynthesis: Constraints on progenitors (Shing-Chi Leung, Ken'ichi Nomoto, 2023);
- A radio-detected type Ia supernova with helium-rich circumstellar material (Erik C. Kool et al., 2023);
- Lensed Type Ia Supernova "Encore" at z = 2: The First Instance of Two Multiply Imaged Supernovae in the Same Host Galaxy (J.D.R. Pierel et al., 2024a);
- Discovery of an Apparent Red, High-velocity Type Ia Supernova at z = 2.9 with JWST (J.D.R. Pierel et al., 2024b).

6. Nuclear Reactions in Stars

As I noted in Section 4, Starrfield, Iliadis & Hix (2016) reported on the effects of improving both the nuclear reaction rate library and including a modern nuclear reaction network in their one-dimensional, fully implicit, hydrodynamic computer code for describing both the recent advances in our understanding of the progress of the outburst and outline some of the puzzles that are still outstanding in the study of the thermonuclear runaway and the CNe outbursts.

For this reason it seems appropriate to me to spend a few words on the nuclear reactions in the stars.

It is difficult to date the beginning of the history of the study of the nuclear reactions in stars. However, Salpeter (1952a,b), Hoyle (1954), Cameron (1955), and Hoyle & Schwarzschild (1955) indicated that the stable elements will be synthesized from hydrogen in the interior of evolving stars. Fowler, Burbidge, G.R. & Burbidge, E.M. (1955) in their important paper on *Stellar Evolution and the Synthesis of the Elements* discussed the problem of transformation of hydrogen into helium by the pp-chain and CN-cycle. Fowler & Greenstein (1956) discussed on the *Element-Building Reactions in Stars*, mainly with the synthesis of the $\sim 2\%$ by mass of the elements heavier than He, which they loosely call "metals".

By using the table of the relative abundances of the elements compiled by Suess & Urey (1956), and the relative plot, Frank-Kamenetskii (1959) deeply discussed on *The Origin of the Chemical Elements* remarking on the possible pathways of the synthesis of the elements from the viewpoint of nuclear physics, nuclear reactions, physical conditions in the interiors of stars, the theories of the pre-stellar formation of the elements, the test of the theory of neutron capture, heterogeneous stars, Helium reactions, sources of neutrons in stars, slow and rapid processes of neutron capture, nuclei with maximum neutron excess, the thermonuclear theory of the formation of the elements, scandium: the cosmochemical thermometer, the iron maximum, the bypassed nuclei, the formation of elements in processes of athermal acceleration, the (p,n) and (p,2n) reactions.

The exhaustive review on *Synthesis of the Elements in Stars* by Burbidge, E.M. et al. (1957) can be deemed as the "Bible". All the reactions discussed are strongly dependent on the cross sections.

Therefore, the knowledge of the cross-sections of nuclear reactions occurring in the stars appears as one of the most crucial points of all astroparticle physics. Direct measurements of the cross sections of the ^{3}He(^{4}He,γ)^{7}Be and ^{7}Be(p,γ)^{8}Be reactions of the *pp* chain and ^{14}N(p,γ)^{15}O reaction of the *CNO-cycle* will allow a substantial improvement in our knowledge on stellar evolution.

Wolschin (2003) published a very interesting paper about the history of the "*Thermonuclear Processes in Stars and Stellar Neutrinos*".

An impressive review about nuclear reactions (*the pp chain and CNO cycles*) has been published by Adelberger et al. (2011). They summarize and critically evaluate the available data on nuclear fusion cross sections important to energy generation in the Sun and other hydrogen-burning stars and to solar neutrino production. Recommended values and uncertainties are provided for key cross sections, and a recommended spectrum is given for ^{8}B solar neutrinos. They also discuss opportunities for further increasing the precision of key rates, including new facilities, new experimental techniques, and improvements in theory. This review, which summarizes the conclusions of a workshop held at the Institute for Nuclear Theory, Seattle, in January 2009, is intended as a 10-year update and supplement to the reviews by Adelberger et al. (1998).

It is in the nature of astrophysics that many of the processes and objects one tries to understand are physically inaccessible. Thus, it is important that those aspects that can be studied in the laboratory be rather well understood.

One such aspect are the nuclear fusion reactions, which are at the heart of nuclear astrophysics: they influence sensitively the nucleosynthesis of the elements in the earliest stages of the universe and in all the objects formed thereafter, and control the associated energy generation, neutrino luminosity, and evolution of stars.

At the moment the LUNA (Laboratory for Underground Nuclear Astrophysics) is a new experimental approach for the study of nuclear fusion reactions based on an underground accelerator laboratory.

It is devoted to measure nuclear cross sections relevant in astroparticle physics. It is the most valuable experiment running underground in the Gran Sasso Laboratory of the INFN. Reviews about LUNA experiment have been published by Broggini et al., 2010, 2016a,b, 2017, 2018).

The LUNA experiment deals with reproducing in the laboratory the nuclear reactions that generate most of the energy produced by the stars and that have allowed the synthesis of the elements within the stars and in the early Universe. These reactions are characterized by a very small probability (cross section) to the energies of astrophysical interest and are very difficult to measure in laboratories on the earth's surface where the cosmic background would mask the weak expected signal. In the last 25 years the LUNA collaboration has installed two accelerators in the LNGS (Laboratori Nazionali del Gran Sasso - INFN) underground laboratories and measured some key reactions in the hydrogen combustion cycle and primordial nucleosynthesis. In the near future a new accelerator will be installed that will also enable reactions of helium and carbon combustion cycles to be measured (Prati et al., 2017; Cavanna et al., 2018; Gustavino et al., 2019).

The LUNA collaboration has already measured with good accuracy the key reactions D(p,γ)^{3}He, ^{3}He(D,p)^{4}He and ^{3}He(^{4}He,γ)^{7}Be. These measurements substantially reduce the theoretical uncertainty of D, ^{3}He, ^{7}Li abundances. The D(^{4}He,γ)^{6}Li cross section – which is the key reaction for the determination of the primordial abundance of ^{6}Li – has been measured (e.g. Gustavino, 2007, 2009, 2011a,b, 2012, 2013), as well as that of ^{2}H(α,γ)^{6}Li (Anders et al., 2013), and ^{2}H(α,γ)^{6}Li (Anders et al., 2014).

Other reactions fundamental for a better knowledge of stellar evolution have been studied by the LUNA experiment: e.g. ^{17}O(p,γ)^{18}F (Scott et al. 2012); ^{25}Mg(p,γ)^{26}Al (Strieder et al., 2012) ^{25}Mg(p,γ)^{26}Al (Straniero et al., 2013); ^{17}O(p,γ)^{18}F (Di Leva et al., 2014).

Cavanna et al. (2015) studied with the LUNA experiment the ^{22}Ne(p,γ)^{23}Na reaction that takes part in the neon-sodium cycle of hydrogen burning. This cycle affects the synthesis of the elements between ^{20}Ne and ^{27}Al in asymptotic giant branch stars and novae. They found a new reaction rate a factor of 5 higher than the recent evaluation at temperatures relevant to novae and asymptotic giant branch stars nucleosynthesis.

Depalo et al. (2016) performed direct measurements of the ^{22}Ne(p,γ)^{23}Na resonances with the LUNA experiment. Based on the present experimental data and also previous literature data, an updated thermonuclear reaction rate is provided in tabular and parametric form. The new-reaction rate is significantly higher than previous evaluations at temperatures of 0.08-0.3 GK.

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The $^{17}O(p,\alpha)^{14}Na$ reaction plays a key role in various astrophysical scenarios, from asymptotic giant branch stars to classical novae. It affects the synthesis of rare isotopes such as ^{17}O and ^{18}F, which can provide constraints on astrophysical models. Bruno et al. (2016) performed direct determination of the resonance strength E_R = 64.5 keV of that reaction at the LUNA accelerator. They found a factor of 2 increase in the reaction rate at astrophysical temperatures relevant to shell hydrogen burning in red giant and asymptotic giant branch stars. The new rate implies lower $^{17}O/^{16}O$ ratios, with important implications on the interpretation of astrophysical observable quantities from these stars, as deeply discussed by Straniero et al. (2017).

In order to further remark the importance of LUNA measurement, we would like to mention the crucial problem of the correct prediction of the abundances of the light nuclides produced during the epoch of Big Bang Nucleosynthesis (BBN) which is one of the main topics of modern cosmology. Trezzi et al. (2017) report results about the cross section of the $^{2}H(\alpha,\gamma)^{6}Li$ reaction that controls ^{6}Li production in the Big Bang. The cross section has been directly measured at the energies of interest for BBN for the first time, at center-of-mass energy E_{cm} = 80, 93, 120, and 133 keV. They found that the $^{2}H(\alpha,\gamma)^{6}Li$ thermonuclear reaction rate is even lower than previously reported, thus increasing the discrepancy between predicted Big Bang ^{6}Li abundance and the amount of primordial ^{6}Li inferred from observations.

A general data base for Experimental Nuclear Reaction Data (EXFOR) can be found in: https://www-nds.iaea.org/exfor/exfor.htm.

7. Some Open Questions

Several fundamental questions concerning CVs still remain waiting for a proper answer. Here we will present briefly only some of them.

One of them is the lack of a coherent classification, especially for NLs. On the other hand, in gross features and in most respects, DN and NLs, as well as quiescent novae, are almost indistinguishable, although, in addition to their different outbursts' behaviour, there appear to be some further minor differences which are not yet understood (see Hack & la Dous 1993). The question arises of whether the outburst behaviour, the current basis of almost all classification is really a suitable criterion for sorting CVs in physically related groups. There are also too many exceptions, either systems that do not fit in any particular group or that can be included in several of them, to be able to render the observational behaviour, at least as it is used at the present, suitable.

Could CVs be considered simply gravimagnetic rotators? This should be the most suitable approach for studying them from a physical point of view.

Studies of rotational equilibria of MCVs predict that IPCVs will evolve either into PCVs or into low field strength polars – presumably unobservable, and possibly EUV emitters – depending on their magnetic moments and orbital periods. Indeed, there are systems, like EX Hya-type, having magnetic moment similar to IPCVs above the 'period gap' and comparable to the weakest field AM Her-like systems.

Moreover, the detection of several SW Sex systems having orbital periods inside the so-called 'period gap' opens a new interesting problem about the continuity in the evolution of CVs.

The rare AM CVn stars have extremely short orbital periods, between 10 and 65 minutes, and their spectra show no evidence for hydrogen. They appear to be helium-rich versions of CVs. They are still waiting for a general model. They are probably binary systems of two white dwarfs, but even this is still controversial.

Despite all the work developed during the last decades, the problem of modeling accretion disks in CVs is by no means closed, especially in quiescence. Closely related is the problem of the cause of outbursts. We really do not know which of the present two families of models (Disk Instability Models or Secondary Instability Models) is responsible for the CVs outburst phenomenon, or in which system is each model valid, although Martinez-Pais et al. (1996) gave a contribution in solving this problem at least in the case of SS Cygni; they found some evidence for an increase of the mass transfer rate from the secondary star as the mechanism responsible for symmetric outbursts. Something similar can be said about the super-outburst phenomenon in SU UMa systems.

Gaudenzi et al. (1990), analyzing IUE spectra of SS Cygni, discussed about the outburst production as due to the destruction of the accretion disk. The matter slowly accretes onto the WD. Long and short outbursts correspond to total or partial destruction of the disk, respectively.

Alternatively, could nuclear burning be responsible of the production of outbursts in CVs? Indeed, nuclear burning onto white dwarf' surface was proposed by Mitrofanov (1978, 1980) as a mechanism suitable to generate X-rays in CVs. In spite of this shrewd suggestion, the community of theoreticians did not consider such a mechanism – certainly possible – worthy of taking up a part of their time. However, we believe that this alternative solution in explaining the generation of outbursts in CVs would deserve theoretician community's care. For instance, the white dwarf surface interested in the accretion in the system SS Cygni has been evaluated as 24% of the total (Gaudenzi et al., 2002). There, nuclear burning could occur.

Accretional heating by periodic DN events increases substantially the surface temperature of the WD in CVs (Godon & Sion, 2002). Then, the envelope thermal structure resulting from compression and irradiation should be a crucial component in understanding the envelope structure of a pre–nova WD.

Another problem still open is connected with the classification of CVs in three kinds, namely NMCVs, PCVs and IPCVs. This is, in our opinion, another convenient classification, although artificial, probably not necessary if CVs are studied as gravimagnetic rotators. In this way a smooth evolution of the systems could be responsible of the variations of the gravimagnetic parameters.

Are the IPCVs and PCVs smoothly connected via the SW Sex-like systems placed just in between? SW Sex systems have indeed orbital periods belong to the so-called 'period gap', and then their presence there sure cancel that gap.

Could some systems behave in different ways depending on their instantaneous physical conditions? For this reason they could apparently behave sometimes as PCVs and sometimes as NPCVs.

An example very clear is that of SS Cygni, usually classified as a non-magnetic dwarf nova. It has been detected by the INTEGRAL observatory in a region of the spectrum (up to $\sim$ 100 keV). This emission is very hard to be explained without the presence of polar caps in the WD of the system. Several proofs have been shown and discussed many times by Giovannelli's group in order to demonstrate the Intermediate Polar nature of it (e.g., Giovannelli, 1996, and references therein; Giovannelli & Sabau-Graziati, 1998; 2012a); indeed, SS Cygni shows characteristics of a NMCV, as well as those of IP and sometimes even those of polars, although its position in the $\log P_{spin}$–$\log P_{orb}$ plane is very close to the line where IPs lie.

An extensive discussion about the nature of SS Cyg is reported in Giovannelli et al. (2024b).

Important results are coming from the SPITZER space telescope with the detection of an excess (3-8) μm emission from MCVs, due to dust (Howell et al., 2006; Brinkworth et al., 2007). Gaudenzi et al. (2011) discussed about the reasons of the variable reddening in SS Cyg and demonstrated that this reddening is formed by two components: the first is interstellar in origin, and the second (intrinsic to the system itself) is variable and changes during the evolution of a quiescent phase. Moreover, an orbital modulation also exists. The physical and chemical parameters of the system are consistent with the possibility of formation of fullerenes.

The SPITZER space telescope detected the presence of fullerenes in a young planetary nebula (Cami et al., 2010). Fullerenes are the first bricks for the emergence of the life. Therefore, the possible presence of fullerenes in CVs opens a new line of investigation, foreboding of new interesting surprises.

Further information can be considered in order to better synthetize the open problems in the knowledge of CVs and related objects.

Sion (http://astronomy.villanova.edu/faculty/sion/CV/index.html) states that in the Galaxy we could expect $\approx 10^6$ CVs. One of the big questions that arises is: "can all of the observed CVs and the phenomena associated with them be understood in terms of a single unified picture?" Other questions relate to the relative probabilities that CVs will be observed at particular stages in their evolution, and how the observations of CVs at the current epoch can be used to determine their ultimate fate.

To address these questions Nelson (2012) and Goliasch & Nelson (2015) have undertaken a massive computational effort to theoretically simulate the evolution of most of the possible CVs that could be produced by nature. The temporal evolution of 56,000 nascent CVs was followed over an age of 10 billion years using the MESA stellar evolution code. According to Nelson, "*This is the most ambitious analysis of the properties of an entire CV population that has ever been undertaken. The whole project required several core-years of CPU time*."

While many of the results confirmed what had already been inferred about the properties of CVs, there were a number of surprises including the identification of a number of previously unexplored evolutionary pathways. But, as expected, a sharp bifurcation was found between nascent CVs that evolved to produce double white-dwarf binaries (including ones containing helium and hybrid white dwarfs), and ones that continuously transferred mass over the lifetime of the universe. In addition, the predictions of the theoretical simulations were in good general agreement with the observations of CVs with reasonably well-measured properties.

What was surprising was the large number of short-period "ultracompact" binaries (AM CVn stars) that were produced and, especially, the enormous depletion of carbon relative to nitrogen and oxygen that is predicted at certain epochs for evolved systems. As Nelson points out, "*It seems that nature has provided us with a unique way to identify CVs that descended from a highly evolved state based on their carbon abundances. There is already some observational evidence to suggest that there is a significant depletion of carbon in certain CVs. This could be a really critical test that will allow us to infer the lineage of some CVs and predict what their fate will be*".

The paper by Otulakowska-Hypka, Olech & Patterson (2016) present a statistical study of all measurable photometric features of a large sample of dwarf novae during their outbursts and superoutbursts. They used all accessible photometric data for all their objects to make the study as complete and up to date as possible. Their aim was to check correlations between these photometric features in order to constrain theoretical models which try to explain the nature of dwarf novae outbursts. They managed to confirm a few of the known correlations, that is the Stolz and Schoembs relation (Stolz & Schoembs, 1984), the Bailey relation (Bailey, 1975) for long outbursts above the period gap, the relations between the cycle and supercycle lengths, amplitudes of normal and superoutbursts, amplitude and duration of superoutbursts, outburst duration and orbital period, outburst duration and mass ratio for short and normal outbursts, as well as the relation between the rise and decline rates of superoutbursts. However, they question the existence of the Kukarkin-Parenago relation (Kukarkin & Parenago, 1934) but they found an analogous relation for superoutbursts. They also failed to find one presumed relation between outburst duration and mass ratio for superoutbursts. This study should help to direct theoretical work dedicated to dwarf novae.

Szkody & Gänsicke (2012) provided a list of unanswered problems and questions and references for seeking additional information. Indeed, while the general evolutionary picture and the characteristics of the types of CVs are known at some level, there are major unsolved questions which remain. These include:

1. What is the actual number density and distribution of CVs in the Galaxy?
2. What happens to CVs once they reach the period minimum?
3. What are the detailed physics occurring in the common envelope?
4. What is the correct physics to describe viscosity in accretion disks?
5. What is the correct angular momentum prescription below the gap (besides gravitational radiation) that can account for the observed period minimum spike and the exact period distribution?
6. What causes the period gap?
7. How do Polars form and why are no magnetic white dwarfs in wide binaries observed? Are LARPS (Low Accretion Rate Polars) the progenitors of polars? Is there a difference in the emergence of systems containing magnetic white dwarfs versus non-magnetic?
8. What causes Polars, as well as the novalike disk systems with orbital periods between 3 and 4 hours, to cease mass transfer and enter low states? Are the associated mass transfer variations of the companion stars a general phenomenon among all CVs?
9. Can the white dwarfs in CVs grow in mass?
10. Do CVs contain exoplanets?

    I can add one point more:

11. Do CVs emit gravitational waves?

    A possible answer to this point has been discussed by Poggiani (2017b), who reports that the most probable sources of GWs are AM CVn systems.

In order to answer to these not yet solved problems, a series of biennial Palermo Workshops about "*The Golden Age of Cataclysmic Variables and Related Objects*" has been organized since 2011. The refereed proceedings can be found in Giovannelli & Sabau-Graziati (2012b, 2015a,b), Giovannelli (2017a, 2021a).

8. Conclusions

At the end of this review it appears evident the role of the magnetic field intensity at the surface of the white dwarf in CVs. It was also remarked the importance of studying the evolutionary path of CVs that very probably is a continuous path connecting the so-called NMCVs with MCVs.

Indeed, the detection of several SW Sex systems having orbital periods inside the so-called 'period gap' opens a new interesting problem about the continuity in the evolution of CVs. Are the IPCVs and PCVs smoothly connected via the SW Sex-like systems placed just in between?

In order to fully understand the emission properties and evolution of CVs, the mass–transfer process needs to be clearly understood, especially magnetic mass transfer, as well as the properties of magnetic viscosity in the accretion disks around compact objects. Consequently, the investigation on the magnetic field intensities in WDs appears crucial in understanding the evolution of CVs systems, by which it is possible to generate classical novae (e.g., Isern et al., 1997) and type-Ia supernovae (e.g., Isern et al., 1993).

In those catastrophic processes the production of light and heavy elements, and then the knowledge of their abundances provides strong direct inputs for cosmological models and cosmic ray generation problems.

I want to conclude with a general warning, apparently underestimated, like discussed in Section 6: if we have not experimental information about the cross sections of nuclear reactions occurring in the stars it is hard to describe the correct star evolution.

The LUNA (Laboratory for Underground Nuclear Astrophysics) is devoted to measure nuclear cross sections relevant in astrophysics and astroparticle physics. It is the most valuable experiment running underground in the Gran Sasso Laboratory of the INFN. LUNA experiment provided the measures of the cross-sections of many nuclear reactions occurring in the stars for a better knowledge of stellar evolution.

As I discussed in the introduction, I can state that the Universe is interconnected in all its components: from cosmic network, to clusters of galaxies, to galaxies, to stars, to planets, to living beings, up to the simple bacterium. Therefore even every manifestation of life on our planet is subject to interconnection with all the surrounding environment. I can affirm that the whole Universe is a vital whole interconnected with more or less strong links between the various components, but that certainly exist.

Finally I can conclude with Fig. 20 that clearly explain all the mysteries of our Universe (Giovannelli, 2021b after Giovannelli, 2000), or if you prefer the same attempt written in Fig. 21 (Giovannelli, 2021b). People who are able to read these sentences can understand that "**The truth is written in the book of the Nature. We must learn to read this book**".

The experiments provide the basic alphabet, immersed in an apparently chaotic soup, but necessary to understand the nature. From that soup we must extract words and phrases to compose the book of the nature. In other words, the data coming from the experiments constitute the basic

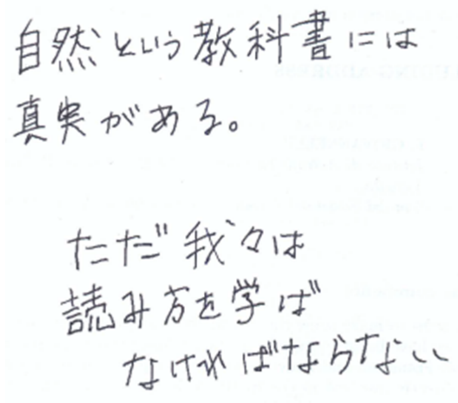

Figure 20: Understanding our Universe (adopted from Giovannelli, 2021b after Giovannelli, 2000).

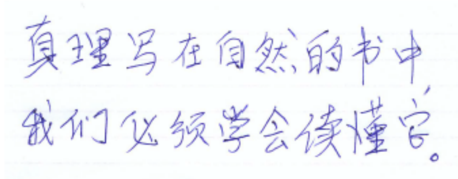

Figure 21: Understanding our Universe (adopted from Giovannelli, 2021b).

alphabet that we use for constructing models that attempt to describe the nature. But we have a lot of models for interpreting the experimental data by the light of science. Depending on the hypotheses the results could run against the experiments. Then, in order to be acceptable, models can take into account and justify **ALL the available data**.

The same concept was expressed in much more incisive terms by Richard Phillips Feynman – Nobel laureate in Physics in 1965 – also known as *The Great Explainer*: **It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong**.

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