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The Hard X-ray Polarization Sensitivity of the Energetic X-ray Imaging Survey Telescope *EXIST*

H. Krawczynski[1], A. Garson III, J. Martin, M. Beilicke,
Physics Department and McDonnell Center fort he Space Sciences, Washington University in St. Louis, 1 Brookings Dr., CB 1105, St. Louis, MO 63130, USA

J. Grindlay, J. S. Hong
Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS 06 Cambridge, MA 02138, USA

G. K. Skinner, S. Sturner
Astrophysics Science Division NASA/GSFC, Code 661, GSFC Greenbelt, MD 20771

for the EXIST team.

Abstract: *EXIST* (Hard X-ray Imaging Survey Mission) is a proposed space borne observatory that combines a wide-field-of-view X-ray telescope (5-600 keV) with a pointed optical/infrared telescope, and possibly with a soft X-ray telescope contributed by Italian collaborators. The primary science drivers of *EXIST* are the study of the high-redshift Universe and the epoch of re-ionization through the detection and follow-up observations of high-redshift Gamma-Ray Bursts (GRBs) at $z \sim 10$, the study of supermassive black holes in galaxies (including heavily obscured and dormant black holes), and the study of stellar mass and intermediate mass black hole populations in the Milky Way galaxy and in the Local Group. In this contribution, we discuss the polarimetric capabilities of the *EXIST* hard X-ray telescope. Based on a pointed 5-day observation (or based on 4 months all-sky survey observations), *EXIST* can detect the hard X-ray polarization of 100 mCrab sources for polarization degrees down to 6%. The wide field of view of *EXIST* will make it possible to measure the polarization of transient events like GRBs and flaring galactic and extragalactic sources. We discuss the scientific potential of the hard X-ray polarimetric measurements. The *EXIST* observations would allow us to (i) obtain qualitatively new constraints on the locale of particle acceleration in the vicinity of compact objects, (ii) gain key-insights into the structure of jets from GRBs and Active Galactic Nuclei, (iii) test high-order QED predictions in the extreme magnetic fields of neutron stars, and (iv) to search for quantum gravity signatures (the helicity-dependence of the speed of light) with unprecedented sensitivity.

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[1] Speaker, email: krawcz@wuphys.wustl.edu

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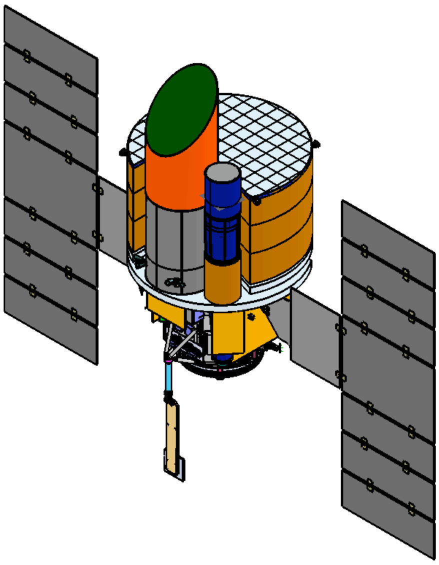

Figure 1: *Design of the EXIST observatory. The high-energy telescope with a detector area of 4.5 m^2 operates over the energy range from 5 keV to 600 keV and can scan the entire sky in two orbits. In this image, only the mask and the collimator (shown in brown) is visible. The EXIST mission includes a 1.1 m diameter infrared telescope (shown in orange) and an optional soft X-ray imager (shown in blue). A detailed description of the EXIST design will be given in [3].*

1. Introduction

EXIST is a proposed medium class mission that combines a High Energy Telescope (HET) with a 1.1 m-class optical/infrared telescope (IRT), and an optional pointed soft X-ray imager (SXI) contributed by the Italian collaborators [1][2][3]. The design of the observatory is shown in Fig. 1. The *EXIST* mission would conduct the most sensitive full-sky survey for black holes on all scales, stellar to supermassive:

• *EXIST* observations and autonomous identification of high-redshift (z ~ 5-15) Gamma Ray Bursts (GRBs) would enable us to study the birth of stellar mass black holes in the very early Universe. The results would shed light on the early history of star formation and on the formation of the very first seed black holes, which grow to become the supermassive black holes at the centers of galaxies. High-resolution spectroscopy of the infrared/optical emission from the GRB, the GRB afterglow, and from the GRB host-galaxy would enable us to study the epoch of re-ionization, i.e. the average neutral hydrogen fraction as function of redshift and the patchiness of the partially reionized intergalactic medium [4].

• *EXIST* would make a census of supermassive black holes (SMBHs) in galaxies to constrain their properties and their role in galaxy evolution. *EXIST*'s sensitivity in the hard X-ray band would make it possible to detect even heavily obscured SMBHs. The wide field of view would enable us to detect dormant SMBHs by recording the transients produced by the final stages of stars being swallowed by the SMBHs [5]. The results will revolutionize our understanding of the co-evolution of galaxies and SMBHs, and will give the definitive answers regarding the origin of the Cosmic Hard X-ray Background and the accretion luminosity in the Universe.

• *EXIST* will acquire detailed time resolved information on the X-ray emission properties of the stellar and intermediate mass black hole populations in the Galaxy and Local Group.

The observations with *EXIST* will complement observations with the Fermi, the James Webb Space Telescope, the Large Synoptic Survey Telescope (LSST), and the Laser

Interferometer Space Antenna LISA by providing both multiwavelength coverage and alerts for unique objects and events.

EXIST is a leading candidate for the Black Hole Finder Probe (BHFP) of NASA's Beyond Einstein Program [6] and is currently under study in the framework of NASA's Advanced Mission Concept Study program in preparation for review by the Astronomy/Astrophysics Decadal Survey (2009-2010). *EXIST* could be launched into a low earth orbit as early as 2017, following the launch of the Joint Dark Energy Mission (JDEM) of NASA and the Department of Energy.

In this paper, we will discuss the capabilities of *EXIST* to measure the polarization of hard X-rays. In Sect. 2 we give a brief technical description of the design of the observatory; in Sect. 3 we discuss polarization measurements with the HET. In Sect. 4, science topics that can be addressed with the *EXIST* polarization measurements are reviewed, and in Sect. 5 the results are summarized.

2. The *EXIST* Observatory – Technical Description

The HET is a wide field of view hard X-ray telescope made of 4.5 m^2 of 0.5 cm thick Cadmium Zinc Telluride (CZT) detectors viewing the sky through a 7.5 m^2 coded mask that can survey the entire sky every two orbits (190 min). With its ~1.8 sr large field of view the HET is an extremely sensitive GRB detector. With its broad energy bandpass, the HET will be able to observe in the first two years of operation alone ~28,000 supermassive black holes largely unhindered by absorption. The detector assembly is made of 11,264 CZT detectors. Each detector has a volume of 0.5×2×2 cm^3 and will be contacted with 1024 pixels at a pitch of 600 μm. With a mean atomic number of ~50, CZT detectors exhibit excellent stopping power and 100 keV photons interact with a probability of 99% with the CZT crystals. The detectors will be read out with a 1024-channel ASIC similar to the ASIC used for the *NuStar* X-ray telescope [7]. Information about the 3-D position of the interaction inside each detector can be derived from the signals induced in several pixels and from drift time information for each pixel. The coded mask has a hybrid design with thin and fine mask elements (1.25×1.25 mm^2) made of 0.3 mm thick Tungsten, and coarse mask elements (15×15 mm^2) made of 3 mm thick Tungsten. The hybrid mask design makes it possible to combine a wide bandpass (5-600 keV) with excellent angular resolution at low energies (E_γ < 150 keV) while avoiding the auto-collimation effects of a thick monolithic mask. The low-energy and high-energy angular resolutions are 2.4 arcmin and 20 arcsec, respectively. The HET is equipped with a graded-Z collimator and an active anticoincidence rear shield that doubles as GRB spectrometer in the 200 keV-5 MeV energy range [8].

The IRT will be equipped with an 1.1 m-class primary mirror. It will operate from the 0.3-2.2 μm wavelength band and will combine imaging with low resolution (~10) and high-resolution (~1000) spectroscopic capabilities. The IRT will be used to obtain positions, redshifts, and high-resolution spectra of GRBs and AGN. The optional soft X-ray imager has

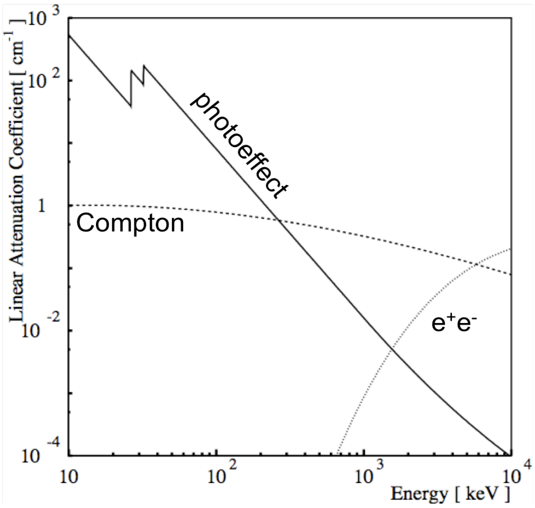

Figure 2: *Linear attenuation coefficients for photoeffect, Compton, and pair production processes in CZT. The large linear attenuation coefficients and the strong dominance of photoeffect interactions over Compton interactions at low energies, set the energy threshold for using CZT detectors as X-ray polarimetry to between 60 keV and 100 keV.*

a 0.3-8 keV bandpass and a collection area of ~1000 cm^2 at 1 keV. The SXI can improve on the source localizations of the HET from 20″ (HET) to <5″ (SXI).

During the first two years of the science operations, the observatory would be used in all-sky survey mode with rapid slews and pointed observations following the detections of GRBs. In the following years, pointed observations of particularly interesting objects would be the default observation mode interrupted by the detection of a GRB in the large field of view of the HET and subsequent follow-up observations with the SXI and the IRT.

3. Hard X-ray Polarimetry with *EXIST* – Estimated sensitivity

3.1 Measurement Principle and General Considerations

The HET can measure the polarization of incident X-rays by making use of the fact that photons Compton scatter preferentially into the direction perpendicular to the orientation of the electric field vector. The polarization analysis uses events with two or more triggered CZT detector pixels, and the azimuthal scattering angle is determined for each event from the two pixels with the largest amplitude signals. The energy threshold of the polarization measurements is determined by Compton kinematics, and by the cross sections for photoeffect and Compton interactions in the CZT. Assuming a scattering angle of 90˚, the energies of the incident photon and the Compton electron are related through the relationship:

$$E_\gamma = \frac{1}{2}\left(E_e + \sqrt{4m_e c^2 E_e + E_e^2}\right).$$

The equation implies that photons with energies E_γ >53 keV can produce Compton electrons with energies E_e exceeding the trigger threshold of the *EXIST* CZT detectors of 5 keV. Additional requirements arise from the photon cross sections in CZT (see Fig. 2). The detection of multi-pixel events with the CZT detectors requires that the mean free pathlength of the

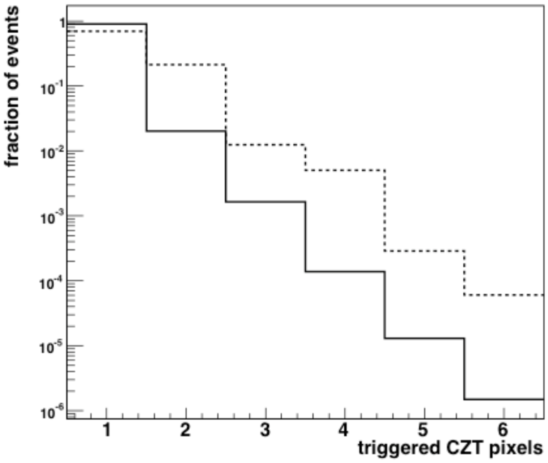

Figure 3: *Trigger multiplicity before and after accounting for charge carrier diffusion in the CZT detectors. Charge sharing increases the number of two-pixel events by a factor of 9.7. The effect of charge sharing thus leads to a substantial "contamination" of multi-pixel events caused by Compton interactions by multi-pixel events caused by photoeffect interactions.*

Compton scattered photons is comparable to the pixel pitch $d = 600$ µm. Equally important, an appreciable fraction of photons should interact in Compton interactions and not only in photoeffect interactions. In the case of CZT, these two requirements result in a low-energy threshold ~80 keV.

Coded mask imaging requires the classification of events as potential source events (possibly triggered by a photon coming from the considered source) or as background events. At primary photon energies below $m_e c^2 / 2 \approx 255$ keV, a high-confidence identification of the first interaction is possible, as such photons loose less than half of their energy in the first interaction. For higher-energy events one can use sophisticated sequencing algorithms to determine the pixel most likely associated with the first interaction [9], and/or restrict the analysis to certain subsets (e.g. to events with all energy deposits in "source pixels" with source exposure, or, with all energy deposits in "background pixels" with no source exposure due to mask blockage).

3.2 Estimate of the Polarization Sensitivity Based on Detector Simulations

We estimated the polarization sensitivity of *EXIST* based on a simulation study with the GEANT-4 code [10], the low-energy electromagnetic processes package GLECS [11], and a in-house developed detector simulation package. Polarized and unpolarized events with photon energies between 30 keV and 500 keV and with a Crab spectrum [12] were simulated. We assume a >100 keV background level of 0.03 cm^{-2} s^{-1}. The photons were assumed to hit the CZT detectors under normal incidence. The detector simulations accounted for the electronic readout noise and for thermal electron diffusion (holes were not simulated). The Einstein relationship for the diffusion constant reads is $D_e = k_B T \mu_e / e$. For an electron mobility of $\mu_e = 1000$ cm^2 V^{-1} s^{-1}, and T = 293.15 K, we get $D_e = 25$ cm^{-2} s^{-1}.

Figure 3 shows the trigger multiplicity before and after including the effect of electron diffusion. It can be recognized that electron diffusion dramatically increases the fraction of ≥ 2 pixel events. The fraction of multi-pixel events caused by "charge sharing" between adjacent pixels should even be higher than the simulated one, as the simulations neglect several effects that enhance the charge sharing effect, e.g. holes tend to induce net charge on more than one

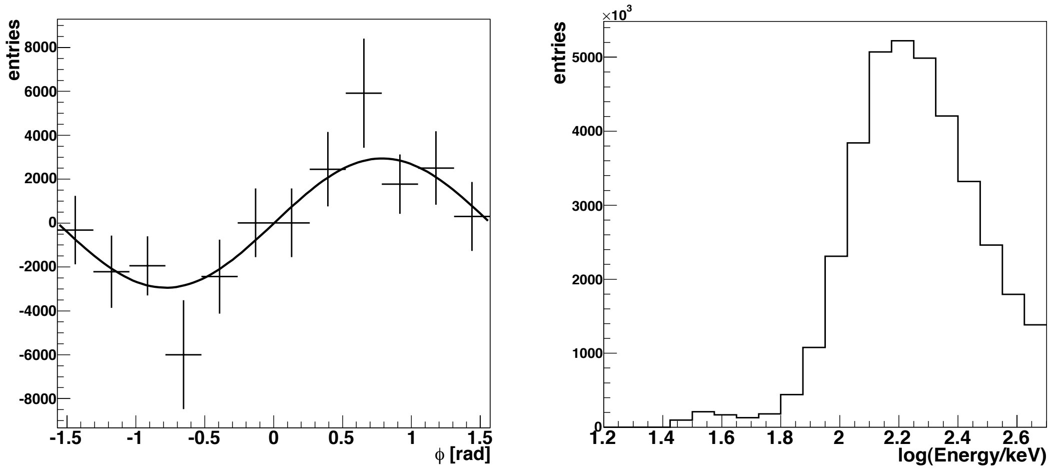

Figure 4: *The left panel shows the net modulation of the distribution of the azimuthal scattering angle for a simulated 5-day observation of a 100 mCrab source exhibiting a polarization fraction of 6% (after the cut for events with the largest energy deposits in horizontally or vertically adjacent pixels). The modulation resembles a sinus-curve with the exception of the bins at* $\boldsymbol{\phi}$ *=± 0.65 which correspond to events with the two highest pixel signals in diagonally adjacent bins. The sinus curve is shown for guiding the eye only. The right hand side shows the energy distribution of the events. Most events that can be used for the polarization analysis have energies between 80 keV and 250 keV.*

pixel, and, electron-electron and hole-hole repulsion lead to additional spreading of the charge cloud (see also [13],[14]).

"Charge sharing events" (events with a single photoeffect interaction that triggered ≥2 pixels due to the effect of charge sharing) contain little information about the polarization of the incident radiation and should be excluded from the polarization analysis. An extremely effective cut is to exclude events from the analysis with the two largest energy deposits in two horizontally or vertically adjacent pixels. The cut suppresses >99% of the charge sharing events and retains 64% of the multi-pixel events caused by Compton interactions leading to energy deposits under ≥2 pixels.

The left panel of Fig. 4 shows the distribution of azimuthal scattering angles (computed from the two pixels with the highest energy deposits) the results of a simulated observation of a source with a flux of 100 mCrab and with a polarization fraction of 6% for 5 days - after subtracting the distribution obtained for an unpolarized signal. The figure demonstrates that the *EXIST* CZT detectors can indeed be used to measure the polarization of X-rays. The right panel of Fig. 4 shows the distribution of the energies of the multi-pixel events surviving the charge sharing suppression cut is shown. Most events have energies in the range from 80 keV to 250 keV. We estimated the sensitivity of the *EXIST* satellite by scaling our results to a detector area of 4.5 m^2. We assume that the analysis uses all detected events with energies below 255 keV for which the location of the first interaction can be determined with a high level of confidence. Using events with higher energies is beyond the scope of the present study. We fit the resulting distribution of azimuthal scattering angles by a template with the phase and the modulation amplitude as free parameters. The sensitivity limit is determined by varying the amplitude of the polarization until the amplitude of the modulation deviates by five standard deviations from zero.

Based on a pointed 5-day observation, *EXIST* can detect the hard X-ray polarization of 100 mCrab sources for polarization degrees down to 6%. Obtaining the same sensitivity in all-sky survey mode would require an observation of 4 months. The wide field of view of *EXIST* will make it possible to measure the polarization of transient events like GRBs and flaring galactic and extragalactic sources. Assuming a GRB with a fluence of 5×10^{-6} erg cm^{-2}, we calculate a minimum detectable polarization fraction of 20%.

The *EXIST* measurements will be subject to much smaller systematic uncertainties than those obtained with current and previous missions, because the number of independent detector elements is very large (11 million pixels), and the distance between pixels is very small (600 microns) compared to the size of the instrument. Neither large scale nor small scale detector and background non-uniformities are expected to lead to large systematic errors: if there are large scale gradients, they will have little impact on the polarization measurements as the latter use only pixels that are rather close to each other. Gain variations of individual pixels of one $0.5\times2\times2$ cm^3 CZT detector can be determined and corrected for with high precision making use of the background data acquired during the mission. In summary, *EXIST* should suffer from systematic uncertainties much less than previously flown instruments owing to the scale of the detector array.

4. Hard X-ray Polarimetry with *EXIST* - Science Topics

Up to now, the Crab Nebula is the only cosmic source with well-measured polarization properties in the X-ray and γ-ray regimes. In soft X-rays, Weisskopf et al. reported a 2.6 keV and 5.2 keV polarization fraction of ~20% and a polarization direction 30˚ oblique to the orientation of the X-ray jet [15]. In the hard X-ray/soft γ–ray regime, Dean et al. measured a high polarization fraction of (46±10)% of the 100 keV – 1 MeV energy range, and a polarization direction parallel to the orientation of the X-ray jet [16]. *EXIST* may find that an increase of the polarization fraction with photon energy is a common phenomenon. The electrons emitting higher energy X-rays lose their energy faster than the electrons emitting lower energy X-rays. As a consequence, the regions responsible for hard X-rays should be more compact than the regions responsible for soft X-rays. The uniform magnetic field in these compact regions should lead to a relatively high degree of polarization. *EXIST* will take hard X-ray polarization measurements to a new level by exploring polarization degrees of a few percent with small systematic errors.

Prime targets for polarization studies with *EXIST* are bright galactic sources. Galactic binary black holes exhibit different emission states. Remillard & McClintock define three states, a thermal state, a hard state, and a steep power law state based on the characteristic of the X-ray energy spectra and on the flux variability characteristics [17]. Owing to its large field of view, *EXIST* would be able to observe the source in the different emission states without missing major flaring events. *EXIST*'s large energy bandpass from 5 keV to 600 keV and excellent timing capabilities are ideally suited to constrain the emission state and to track the evolution of the emission components. At >80 keV energies, the *EXIST* hard X-ray polarimetry observations will shed light on the origin of the non-thermal emission. The *EXIST* polarimetry observations will allow us to test hypotheses about the origin of the hard X-ray emission as jet and/or as emission from a disk corona.

EXIST will be able to scrutinize the polarization of the hard X-rays from mass accreting neutron stars (e.g. Hercules X-1, Cen X-3), young high-field pulsars (e.g. B1509-58), and magnetars. Owing to the emission mechanism and to the propagation of the X-rays through the highly magnetized plasma surrounding the neutron stars, the X-rays from these objects might exhibit polarization degrees of several 10% (e.g. [18][19]). Photon-splitting (a higher order QED effect) is expected to produce strong polarization leading up to a high-energy cut-off [20] in high-field pulsars [21] and magnetars. This effect cannot be observed in terrestrial laboratories and would provide a test of QED in extreme conditions.

X-ray polarization may reveal the inner structure of the jets from gamma-ray bursts (GRBs) [22][23][24][25]. For high polarization fractions, the observations could establish the magnetically dominated character of the jet flow, and would constrain the process of jet formation as well as the central engine. Observations of the polarized X-ray emission from GRBs can be used to constrain fundamental physics beyond the standard model (see [26] for a review), e.g. quantum gravity theories, and other theories (see e.g. [27]). Such observations are not restricted to upper limits: the detection of an energy dependent change of the polarization direction for a large number of different GRBs could give positive evidence for a birefringence of the vacuum. Currently the best limits on the helicity dependent variation of the speed of light come from observations of polarized UV emission from a GRB afterglow [28]. The sensitivity of searches for first order variations of the speed of light improve with the observation frequency squared. The *EXIST* observation could thus improve by a factor of 10^9 over the limits from UV observations, and by a factor of 10^4 over limits derived from X-ray polarimetry observations at ~1 keV with soft-X-ray polarimeters.

EXIST will be able to probe the polarization of hard X-rays from Active Galactic Nuclei in outburst. Of particular interest are blazars (mass-accreting supermassive black holes with highly relativistic jets pointing at the observer), which are strong emitters of continuum emission. The hard X-ray emission is either synchrotron emission or inverse Compton emission from high-energy electrons. In the case of extreme synchrotron blazars [29], the synchrotron emission extends into the very hard X-ray regime. For example, for Mrk 501, the BeppoSAX mission measured a spectral energy distribution with a ``low-energy'' component peaking in the >100 keV energy range [30]. The high-energy component, presumably inverse Compton emission, peaks in the GeV/TeV energy range. Extreme synchrotron blazars show long lasting periods (3 months or more) of intense flaring activity. The *EXIST* observations will assess the structure of the jets in the ``blazar zone'' ~1 pc away from the black hole, and will provide important constraints for models of jet formation. If jets have a strong helical magnetic fields, it might be possible to detect a swing of the direction of the polarization on time scales of $\sim 10\ M_{BH}/(10^8\ M_{\odot})$ days [31].

5. Summary and Conclusions

The *EXIST* hard X-ray survey telescope will have excellent hard X-ray polarization capabilities. The polarization measurements use Compton scattered photons that trigger more than one pixel of *EXIST*'s finely pixilated CZT detectors. The *EXIST* polarization measurements would ideally complement polarization results obtained in the soft X-ray regime with X-ray telescopes using gas pixel detectors [32] and/or time projection chambers [33], and in the γ–ray regime with Compton telescopes like the Advanced Compton Telescope. Owing to its large field of view, *EXIST* will be able to obtain polarization measurements of transient phenomena like GRBs. The polarization measurements would make unique contributions to the astrophysics of compact objects like stellar mass black holes, supermassive black holes, and neutron stars, and to astroparticle physics topics like the detection of high order QED effects in the extremely strong magnetic fields of magnetars and uniquely sensitive tests of Lorentz Invariance.

A dedicated calibration program should be performed to minimize systematic errors. Detailed studies of cross-talk properties (including electronic and weighting potential cross talk), as well as demonstrations that the polarization of signals with zero and non-zero polarization fractions can be measured accurately are of particular interest.

Acknowledgments

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