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The History of the Equatorial Emission in SS433

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The equatorial radio emission recently discovered in SS433 adds a further intriguing feature to what is already a bizarre object. Radio images of SS433 taken over the last 25 years were examined to find that evidence for the existence of the emission exists even in the early images. The extended emission is found in 18 out of 78 separate observations, with a higher detection rate in recent years, reflecting improving imaging capability of interferometer arrays. The position angle of the emission changes, being on average perpendicular to the precession axis of the jets and varying over a similar range to that of the jets, however there is not a close relationship between the jet and equatorial emission position angle. This suggests that if the emission is formed by a precessing equatorial wind then the wind velocity must vary. Alternatively the emission could be due to colliding back flow from the jets.

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1. Introduction

SS433 is famous for its moving optical lines [13] and precessing radio jets [23,10]. Recently [16,17,1,21] radio emission was found in a direction roughly perpendicular to the precession axis (position angle 100^o [10,23,24]) of the radio jets, in diffuse 'ruff' structure. The observations of Blundell et al. (2001) [1] suggest that the emission is thermal in origin, though with a high brightness temperature, though Paragi et al. 2001 [18] find that the emission in compact regions may be non-thermal. The existence of an excretion disk surrounding the system has been suggested [3], and the disk may manifest itself by this equatorial emission. If so we would expect the emission to be persistent, and be present in earlier images made of the jets in SS433. High resolution radio imaging fidelity has improved greatly over recent years, with the advent of phase referencing, better calibration and imaging algorithms and improved uv-plane coverage with instruments like the VLBA and EVN. The early images were originally interpreted conservatively, and so features might have been missed. All the published images of SS433 were therefore examined with the benefit of hindsight.

2 The Archive

A total of 78 epochs of radio maps were found in the literature from 1979 to 2003. Most of the observations were made using VLBI, MERLIN or the VLA as stand alone instruments, though there are several cases where observations were made with multiple arrays. The beautiful VLBA movie of Mioduszewski et al (http://www.aoc.nrao.edu/~amiodusz/) [21] has been counted as one epoch here, though really there were 39 separate images, however the equatorial emission was present in nearly all the images. The discovery paper for the radio jets only used a single baseline interferometer and so earlier (1976) images are not available [23]. The 78 images used are listed in table 1, together with the observing frequency, the instrument and the reference. The 18 cases where there is evidence of equatorial emission indicated by an asterisk in column 1. The evidence varies from a slight extension in the contours in a general N-S direction near the centre of the object, to clearer cases where there is discrete emission. An example of the former can be seen in figure 1, where is there is emission to the South of the core. A case where there is clear emission on the North and South of the core region is shown in figure 2, using combined MERLIN and EVN data. It is clear that the equatorial emission was indeed present in the images, though it is not surprising it was missed given the difficulties of mapping low declination sources where the uv coverage of each baseline is dominantly E-W. The fraction of epochs were the emission is present is clearly higher in recent years, reflecting improvements in the imaging capability of radio interferometers.

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Table 1 Radio Observations of SS433

Date of Observations	Frequency GHz	Instrument	Reference
22/07/1979	1.5	VLA	Gilmore & Seaquist 1980 [6]
22/07/1979	4.9	VLA	Gilmore & Seaquist 1980 [6]
08/09/1979	4.9	VLA	Hjellming & Johnston 1981 [10]
16/09/1979	4.9	VLA	Hjellming & Johnston 1981 [10]
07/12/1979	4.9	VLA	Hjellming & Johnston 1981,1981b [10,11]
09/01/1980	5	EVN	Schilizzi et al. 1982 [22]
02/02/1980	0.4	MERLIN	Spencer 1984 [24]
20/02/1980	4.9	VLA	Gilmore et al 1981 [7]
07/03/1980	4.9	VLA	Hjellming & Johnston 1981,1981b [10,11]
05/04/1980*	4.9	VLA	Hjellming & Johnston 1981,1981b [10,11]
19/05/1980*	4.9	VLA	Gilmore et al. 1981 [7]
20/06/1980	4.9	VLA	Hjellming & Johnston 1981,1981b [10,11]
14/08/1980	1.7	MERLIN	Spencer 1984 [7]
02/09/1980	1.7	MERLIN	Spencer 1984 [7]
03/10/1980	5	EVN	Romney et al. 1987 [20]
05/10/1980	2.3	VLBI	Niell et al. 1982 [15]
12/10/1980	1.7	MERLIN	Spencer 1984 [24]
25/10/1980	1.7	MERLIN	Spencer 1984 [24]
16/12/1980	1.4	EVN	Romney et al 1987 [20]
13/02/1981	2.3	VLBI	Niell et al. 1982 [15]
15/02/1981	1.7	EVN	Romney et al. 1987 [20]
11/04/1981*	5	EVN	Romney et al. 1987 [20]
17/05/1981	2.3	VLBI	Niell et al. 1982 [15]
26/05/1981	5	EVN	Romney et al. 1987 [20]
01/06/1981	5	EVN	Romney et al. 1987 [20]
30/08/1981*	1.4	EVN	Romney et al. 1987 [20]
09/12/1981	5	EVN	Romney et al. 1987 [20]
04/04/1982	5	MERLIN	Spencer & Waggett 1984 [25]
12/04/1982	5	MERLIN	Spencer & Waggett 1984 [25]
20/04/1982	5	MERLIN	Spencer & Waggett 1984 [25]
28/04/1982	5	MERLIN	Spencer & Waggett 1984 [25]
14/05/1982	5	MERLIN	Spencer & Waggett 1984 [25]
25/05/1982	15	VLA	Heavens et al. 1990 [9]
27/05/1982	5	MERLIN	Spencer & Waggett 1984 [25]
13/06/1982	5	MERLIN	Spencer & Waggett 1984 [25]
02/07/1982	5	MERLIN	Spencer & Waggett 1984 [25]
13/06/1984	1.4	EVN	Fejes 1986 [4]
17/05/1985	5	EVN	Vermeulen et al. 1987 [30]
19/05/1985	5	EVN	Vermeulen et al. 1987 [30]
21/05/1985	5	EVN	Vermeulen et al. 1987 [30]
23/05/1985	5	EVN	Vermeulen et al. 1987 [30]
25/05/1985	5	EVN	Vermeulen et al. 1987 [30]
27/05/1985	5	EVN	Vermeulen et al. 1987 [30]
15/03/1986	1.7	EVN	Fejes et al. 1988 [5]
23/05/1987	5	EVN	Vermeulen et al. 1993 [31]
25/05/1987	5	EVN	Vermeulen et al 1993 [31]

27/05/1987	5	EVN	Vermeulen et al 1993 [31]
29/05/1987	5	EVN	Vermeulen et al 1993 [31]
31/05/1987	5	EVN	Vermeulen et al 1993 [31]
02/06/1987	5	EVN	Vermeulen et al 1983 [31]
17/07/1987*	5, 15	VLA	Stirling et al. 2004 [29]
30/04/1988	1.7	MERLIN	Spencer et al. 1993 [26]
10/05/1988	1.7	MERLIN	Spencer et al. 1993 [26]
19/05/1988*	1.7	MERLIN	Spencer et al. 1993 [26]
10/06/1988	1.7	MERLIN	Spencer et al. 1993 [26]
28/06/1988	1.7	MERLIN	Spencer et al. 1993 [26]
07/12/1991	5	MERLIN	Stirling et al. 2002 [28]
12/12/1991*	5	MERLIN	Stirling et al. 2002 [28]
22/12/1991	5	MERLIN	Stirling et al. 2002 [28]
04/01/1992*	5	MERLIN	Stirling et al. 2002 [28]
25/09/1993*	1.7	MERLIN	Halai 2001 [8]
19/04/1994	1.6	VLBA	Stirling et al. 1997 [27]
21/04/1994	1.6	VLBA	Stirling et al. 1997 [27]
06/05/1995*	1.6	VLBA	Paragi et al. 1999 [17]
15/02/1997	5	MERLIN	Stirling et al 2004 [29]
07/03/1998*	5	VLBA/MERLIN	Blundell et al. 2001 [1]
26/03/1998	15	VLBA	Paragi et al. 1999 [17]
18/04/1998	22	VLBA	Paragi et al. 1999 [17]
22/05/1998*	5	VLBA	Paragi et al. 2002 [19]
06/06/1998*	1.7	EVN/MERLIN	Paragi [19], Stirling [29]
16/06/1998*	5	EVN	Paragi et al. 2002 [19]
13/02/2000*	1.7	VLBA/EVN/MERLIN	Paragi et al. 2002 [19]
20/02/2000*	1.7	VLBA/EVN	Paragi et al. 2002 [19]
27/03/2000	5	MERLIN	Stirling et al. 2004 [29]
27/05/2000*	1.7	VLBA/EVN	Paragi et al. 2002 [19]
14/10/2001	5	MERLIN	Stirling et al. 2004 [29]
10/07/2003	4.9	VLA	Blundell & Bowler 2004 [2]
06/08/2003*	1.5	VLBA	Mioduszewski et al. in prep

3 The Properties of the Equatorial Emission

Examination of the images shows that the position angle of the equatorial emission changes from epoch to epoch, for example the emission in figure 2 is in a position angle (PA) of 0 ± 2^o, whereas the emission in the images from the Mioduszewski VLBA [21] movie is in PA -20 $\pm 10^o$. Figure 3 shows a plot of the PA *vs* modified Julian date (JD-2400000.5). There is no clear periodic pattern, though this not surprising given that the 52 cycles of the 162.5 day precession period in the data are seriously under-sampled. Figure 4 shows a histogram of the positions angles, it is notable that the mean position angle (10.4 ± 3.0^o) is perpendicular to the mean jet axis (PA 100^o) and with a similar range (-20 to 35^o compared with 80 to 120^o). This strongly suggests that the equatorial emission is related in some way to the precessing jets. However figure 5 shows that the observed position angle does not appear to correlate with the position angle of the inner jets at the observation date (using the Margon (1984) [14] ephemeris.

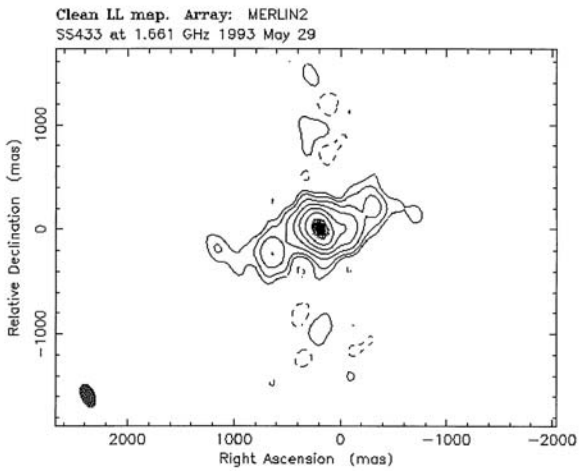

Figure 1 MERLIN image of SS433 at 1.66 GHz taken on 25 October 1993. Note the slight extension to the South of the core. The discrete knots ~ 1 arc sec to the N and S of the core are likely to be side-lobes and an artefact (from [8]).

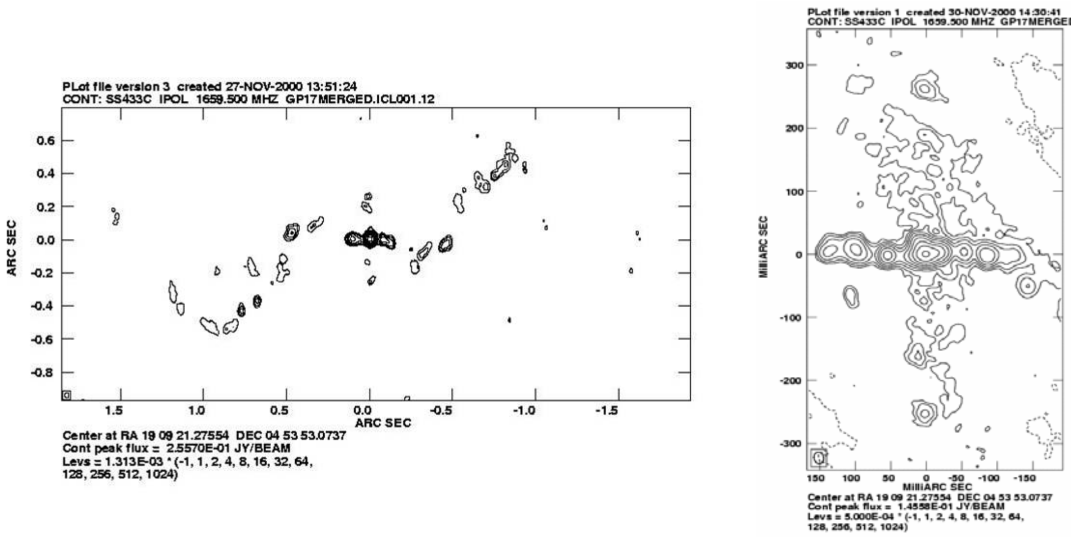

Figure 2 Combined MERLIN and EVN images of SS433 at 1.66 GHz, using data taken on 6 June 1998. The map on the left shows the large scale structure, a higher resolution map of the central region is shown on the right. These maps were produced by A. Stirling (priv. comm.) from data also imaged by Paragi et al. 2002 [19] and Stirling et al. 2004 [29].

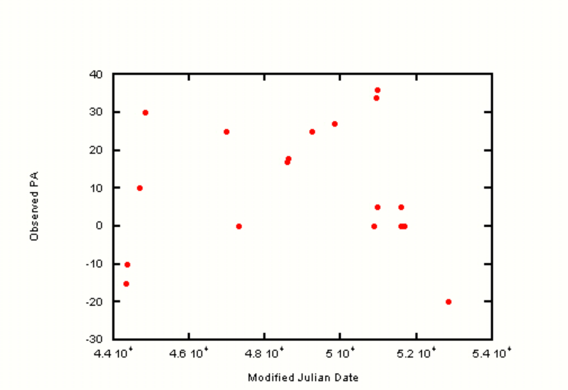

Figure 3 Plot of the position angle of the equatorial emission *vs* date.

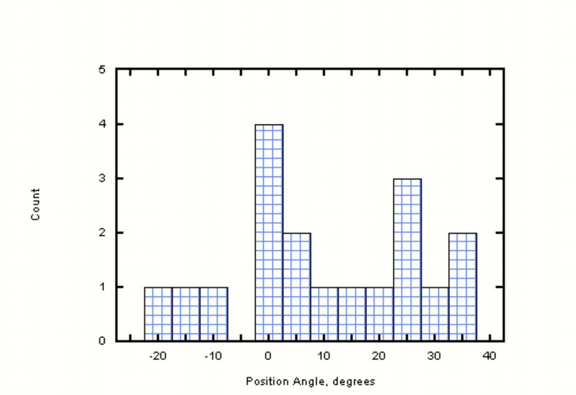

Figure 4 Histogram of the observed position angles of the equatorial emission.

There is also no correlation if the equatorial emission had been ejected at a previous date to the observations: time delays for each observation were calculated from angular size estimates taken from the published images and assuming velocities of 5000 and 10000 km sec^{-1}. Corresponding inner jet position angles were found from the ephemeris using the corrected date, but comparison with the observed PA also has a random scatter.

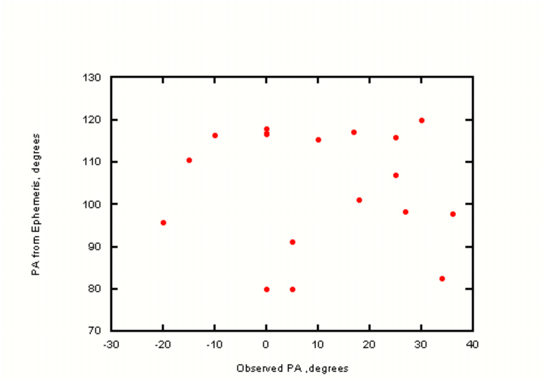

Figure 5 Plot of the observed position angle *vs* the expected position angle of the inner jets derived from the Margon 1984 ephemeris.

4 Discussion and Conclusions

On the precessing jet model [14] the inner disk around the compact star precesses due to tidal torques, and so we would not expect to see precession of an anisotropic wind from the companion star. However, the fact that the position angle does change lends support to the presence of a disk wind [3] where the disk and wind also precess. We would expect to see a delay between the jet ejection angle (and by inference the inner disk PA) and the outer disk PA and disk wind direction. The lack of a clear correlation with the jet direction also suggests that if a wind is indeed the source of the equatorial emission then the wind velocity cannot be constant.

Examination of the images shows a few cases where we can perhaps relate the position angle of the jet to the observed equatorial emission PA. In figure 2, the equatorial emission is perpendicular to the jet at a position ~0.5 arc sec from the core. Other cases show that the PAs are perpendicular to each other at distances up to 2 arc sec. These angular separations correspond to delays of 50 to 200 days (given the 0.26c jet velocity and a distance of 4.8 kpc) between the ejection of an equatorial wind and hence corresponding velocities of 16000 and 4000 km sec^{-1}. With such high wind velocities it is not surprising that high brightness non-thermal knots occur, formed by particle acceleration in strong shocks.

An alternative explanation of the equatorial emission comes from hydrodynamic studies of bipolar nebulae [12]. The colliding backflow from ejected clumps in high velocity jets can cause enhanced densities in the equatorial plane (essentially where the two bow shocks from each jet in a two-sided jet structure meet). Simulations have shown that the density enhancement can be high in a circumstellar atmosphere where the density (perhaps in a wind) falls off as the inverse square of the radius (Smponias, in prep.).

Archive data have shown that the anomalous emission aligned roughly along the equator of SS433 was detected in the past. It does not always seem to be present; this could be due to mapping fidelity problems, though the MERLIN observations of Stirling et al. 1992 showed that the emission, though clearly present on 12 December 1991, was not present 10 days later. Also the VLBA movie by Mioduszewski shows variable intensity for the equatorial emission. This emission is undoubtedly a feature of SS433, to add to the list of its bizarre properties.

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