Stellar VLBI

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Reliable high-angular resolution maps of 5 active binaries at several epochs have been produced so far by the VLBI technique including circular polarisation maps. A double lobe radio structure exhibited at some epochs at least is common to these 5 different systems mapped by VLBI. The most explicit results at present are the double lobe radio structure found for the eclipsing binary Algol and for the dM5.5e star UV Ceti B. The VLBI structure and the orbital elements of these two systems suggest that there is a dipolar magnetic field aligned with the rotation axis of the active star. The two radio emitting regions observed are above the two polar caps. The extents of the corresponding coronae are as large as 4.4 stellar radii for the dMe star UV Ceti B and only 2.6 stellar radii for the subgiant of Algol.

1. Introduction

The discovery of radio emission from the stellar binaries Algol and β Lyrae by Wade & Hjellming (1972) at the NRAO Greenbank interferometer opened a new field in radio astronomy devoted to stellar emisson. This field rapidly becomes important for the physics of stellar coronae in connection with the study of coronal emission from the Sun. The total radio luminosity of active stars is 10^{13} - 10^{18} ergs/s/Hz or 10^{2} - 10^{7} times larger than the gradual solar flares. Early surveys showed that close binaries are the most active among stars and that their radio emission is highly variable (Spangler et al 1977). Fractional circular polarization of 10-20 % was also measured in early observations and interpretated as evidence of gyrosynchrotron emission from energetic electrons with Lorentz factor of ~ 10 ($\sim$ a few Mev) radiating in magnetic field of a few tens of Gauss (Owen and Jones 1976). This interpretation still holds today but the geometry of the magnetic structure and the mechanisms that produce the high-energy (non-thermal) and thermal electon populations are still opened questions today. This is critical to assess, for instance, if the radio emitting region is well anchored in such a system and can be used as a positionally stable tracer of the motion of the system with the scope of detecting by VLBI astrometry the wobble caused by an extrasolar planets orbiting around it.

Active close binaries have short orbital periods of usually a few days and separation of only a few tens stellar radii, many belongs to the RS CVn class or to the Algol type. The stellar components have various spectral types, from B to M, and belong to several classes: main sequence, subgiant and giant. Most active binaries are tidally locked and synchronous and, consequently, their rotation rate is much higher than the rate of a single star with the same spectral type. The active component is thought be the star of type later than F with a deep convective zone. Currents developed in their interiors combined with the high rotation rate and differential rotation to produce magnetic fields.

Young single stars, pre-main sequence T Tauri and red dwarfs (dMe), are fast rotators too because of their yougth and exhibit a non-thermal radio activity (André et al 1991). A few evolved stars of the FK Com type are also active because they became fast rotators when forming from a binary system through coalescence.

In summary, fast rotation and spectral type later than F (deep convective and differential rotation) are the properties common to the non-thermal radio emitters.

X-ray counterparts are generally associated with the stars that are active in radio with X-ray luminosity as high as $10^{29} - 10^{31}$ ergs/s. This activity is thought to come from large coronal structures that are magneticly confined with thermal electrons whose temperature is 10^6 and/or 10^7 K. The X-ray and radio luminosities are correlated over 10 orders of magnitude from solar microflares to FK-Com type star (Benz and Güdel 1994). However, the relationship between the non-thermal and thermal electron populations, responsible for the radio and X-ray emissions, respectively, is not understood.

The observations show that the magnitude of the fractional circular polarisation in the total flux density is stronger when the inclination of the orbital plane on the sky is lower (Mutel et al 1987). It is noticeable also that the sense of circular polarisation remains unchanged for several years. These properties are consistent with a dipolar magnetic structure to first order that would be associated with a single star of the system.

2. Brief history of stellar VLBI

The first high-angular resolution observation of a star was carried out on Algol by Clark, Kellerman and Shaffer (1975) with the VLBI technique between NRAO-140 foot antenna and Haystack antenna at 7.8 GHz. In the late 70's, VLBI observations were conducted on UX Ari between Arecibo and NRAO140 Greenbank by D.C. Backer and on HR1099 by G. Resh but never published. The weakness (milliJansky range) and variability (hour time scale) of the non-thermal radio emission of stars made those pionoreering observations difficult, in the early days of VLBI in the 70's. The first systematic campaign of VLBI observations of stars was engaged in 1982 in support of the ESA mission Hipparcos to astrometrically linked the future Hipparcos stellar catalogue to the extragalactic radio sources. This campaign used the recently completed Mark III recording system developed by Haystack Observatory for NASA and included about 80 observation sessions throughtout 1994. The increased recorded bandwidth of the Mark III system improved sensivity by $\sqrt{14}$ and was combined with the largest antennas for this campaign. The 64-m antennae of the NASA tracking stations at Goldstone, Madrid and Tidbinbilla (later 70-m) and the NRAO phased-VLA (125 meter equivalent) were decisive in participating in VLBI arrays with 30-m antennas. The use of the phase-referencing technique from October 1984 and on was also a key factor in increasing the integration time from 10 minutes to a few hours at 8.4 GHz (Lestrade et al 1990). Other individual projects on the EVN and the US network were conducted on several stars. The VLBA and JIVE facilities make those projects technically easier now and provide a powerful means of investigation of these stars.

3. VLBI images of stars

The majority of the VLBI data measured on stars have been discussed via visibility functions to derive radio source size and brightness temperature using a Gaussian brightness distribution model. These analyses were important to establish directly that the gyrosynchrotron process is responsible for the radio emission mechanism and to recognize that the emitting region could be larger than the whole binary system.

VLBI maps of stars are still only a few. They have been produced for the RS CVn binaries UX Ari (Mutel et al 1985, Franciosini et al 1999, Beasley et al 2000), HR1099 (Ransom et al 2000a), Algol (Mutel et al 1998), IM Peg (Ransom et al 2000b), for the dMe stars UV Ceti B (Benz et al 1998), YZ Cmi and AD Leo (Pestalozzi et al 1999). We shall review below the main results from these papers.

VLBI maps have also been produced for the X-ray stars LSI61303 (Paredes et al 1998), CygX1 (Stirling et al 2000), SS433 (Vermeulen 1989) and GRS1915+105 (Dhawan & Mirabel in preparation), for the Wolf-Rayet binary WR140 (Beasley et al in preparation) and a polarisation VLBA map has been produced for the Mira variable TX Cam (Kemball

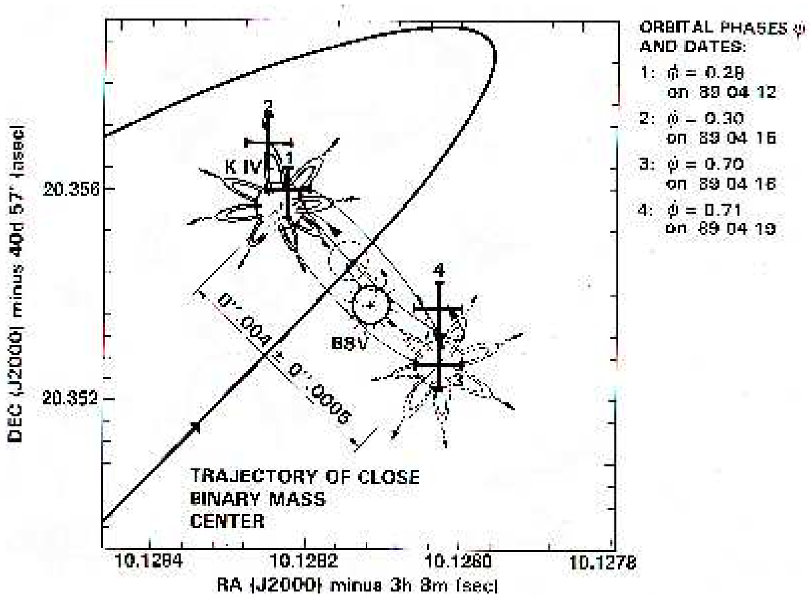

FIGURE 1. Time-sequence of the VLBI positions (crosses) of the radio emitting region in the close binary Algol during two consecutive orbital revolutions from Lestrade et al 1993

& Diamond 1997). We are not reviewing these results here but they have been among the highlights of VLBI stellar work.

3.1. **Algol**

Algol is a close binary made of a subgiant K0 (R=3.53 $R_\odot$) and a main sequence B8 (R=2.89 $R_\odot$) with an orbital period of 2.9 days. The radio emitting region in Algol is associated with the subgiant K0 as shown by VLBI astrometry in tracking the orbital motion of this eclipsing close binary over two consecutive orbital revolutions (Figure 1 from Lestrade et al (1993)). From these VLBI observations, the node of the orbital plane was also determined ($\Omega = 52 \pm 5°$) and used by Mutel et al (1998) to interpretate the VLBA map they obtained that showed a double lobe radio structure for Algol (Figure 2 Left ; Mutel et al 1998). The orientation of this radio structure is close to the rotation axis of the stars assumed perpendiclar to the orbital plane. In addition, their map showed that the two lobes are circularly polarised in opposite directions. This led Mutel et al (1998) to propose that the subgiant K2 has a predominantly dipolar magnetic field close to the rotation axis of the star and that the two radio emitting regions are above the two poles of the subgiant K2. The separation between the two lobes is 2.6 K0 stellar radii and is an indication of a large corona.

3.2. **UV Ceti B**

The binary UV Ceti is composed of two main sequence dM5.5e stars, has an orbital period of 26.5 years and is well separated. This system is young (6×10^8 years) and still relatively close to the zero main-sequence age. Benz et al (1998) have obtained the VLBA map of UV Ceti B in Figure 2 (Right) that shows also a double lobe structure with an orientation that is very close to the projected axis of rotation of the star. The corresponding corona is large since the radio centroids between the two lobes are separated by 4.4 stellar radii. There is no circular polarization information in their VLBA map but the VLA indicates that the total flux density is 10 % right circular. Benz et al (1998) also shows that one of the lobe over the course of the 5 hour experiment disappears while

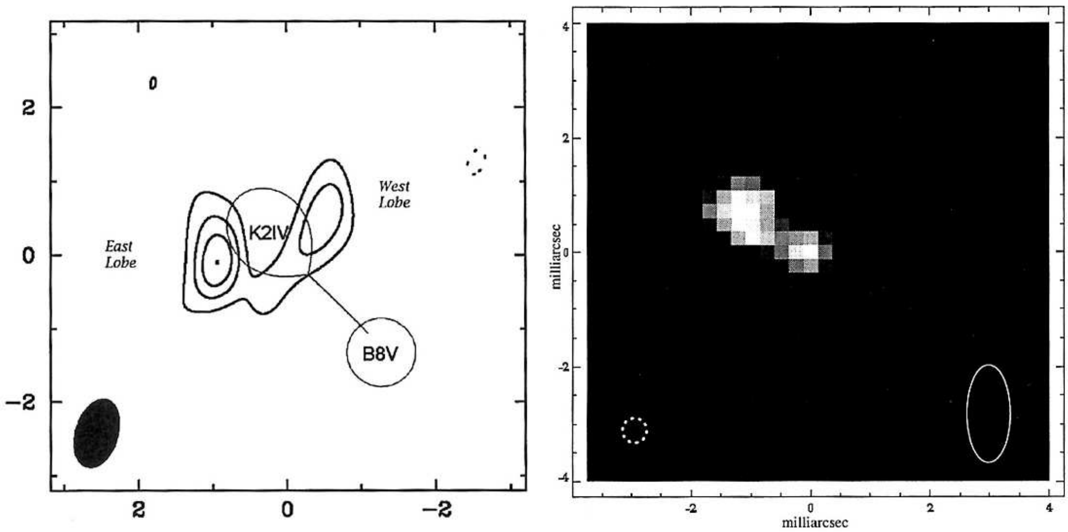

FIGURE 2. *Left:* VLBA circular polarisation map of Algol showing a circularly polarised double lobe structure that is associated with the regions above the two poles of Algol (Mutel et al 1998). *Right:* VLBA image of UV Ceti B (Benz et al 1998)

the flux density of the other stays roughly constant. It is striking that the structure of UV Ceti although variable is reminiscent of the two radio lobes found for Algol by Mutel et al (1998). The same polar cap model might be at work in these very different stars that are components of very different binaries.

3.3. **UX Ari**

The RS CVn binary UX Ari is composed of a subgiant K2 (6 $R_\odot$) and a main sequence G5 (0.93 $R_\odot$) with an orbital period of 6.4 days. It is the most studied RS CVn binary with HR1099. The first VLBI map of UX Ari by Mutel et al (1985) showed a "core-halo" radio structure about twice as large as the size of the binary system during an outburts with most of the flux density concentrated in the halo. Beasley and Güdel (2000) have obtained a total intensity VLBA map of UX Ari that shows also a halo about twice as large as the system but during quiescence. They also obtained a VLBA map showing change in the sense of circular polarisation across 1-2 milliarc. This extent is comparable to the separation of plausible footpoints of a magnetic loop anchored in the subgiant K2 whose angular diameter is 1.1 mas. Franciosini et al (1999) have a sequence of three total intensity VLBI maps of UX Ari made over 5 days, *i.e.* within an orbital revolution. These 3 maps show significant change of structure from a circular brightness distribution to a double lobe structure. Lestrade (in preparation) has also a very similar sequence of VLBI structures over 4 days. Finally, the post-fit astrometric residuals of 10 VLBI observations of UX Ari conducted between 1983 and 1994 for Hipparcos are plotted on the sky with the projected relative orbit of the binary in Figure 3. The elongated distribution of these residuals suggests that the node of the orbit can be fixed to 60°. (Figure 1 of Lestrade (1996) shows a similar plot but the orbit semi-major axis used is erronous). The residual positions are also plotted versus orbital phase in Figure 4. The astrometric fit includes adjustment of coordinates, of proper motion, of acceleration and trigonometric parallaxe (see details in Lestrade et al 1999). The correlation between the orbital motion and these residual positions is not straighforward but a possible systematic trend exists and calls for confirmation with further observations. All these results (total

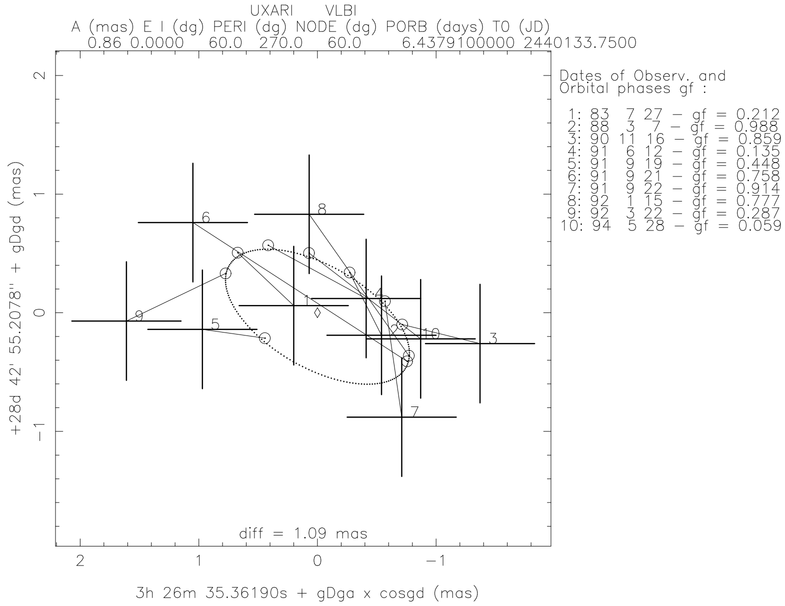

FIGURE 3. VLBI residual positions of UX Ari plotted on the sky. The projected relative orbit of the binary is superimposed. The node has been fixed to 60° as suggested by the elongated distribution of the residuals.

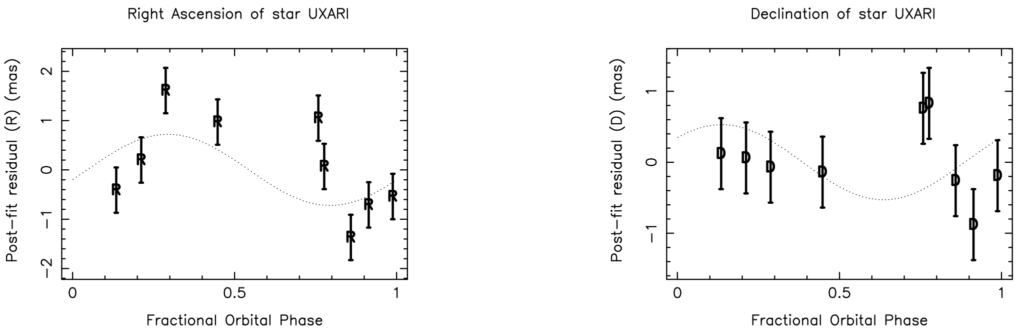

FIGURE 4. VLBI residual positions of UX Ari between 1983 and 1994 plotted versus orbital phase. The dotted line is the projected right-ascension (R) and declination (D) of the secondary K2 IV relative to the primary G5 V (node is fixed as in Figure 3)

intensity and polarisation VLBI maps and VLBI astrometry) could be used to constrain the model proposed by Triglio et al (1998) and by Franciosini et al (1999) where two loops (meridian and equatorial) are attached to the subgiant's face opposite to the G5 V, *i.e.* outwards the orbit area. Already, Triglio et al (1998) successfully explained a systematic trend in their single-dish flux density monitoring by invoking absorption of the radio emission from the subgiant K2 by the corona of the G5 V at orbital phase 0.5 (conjonction). Franciosini et al (1999) have successfully simulated the structue changes of their sequence of 3 VLBI images with this model. It requires magnetic loops attached to the subgiant that are as high as 20 $R_\odot$ while the largest loops on the Sun are about 1 $R_\odot$.

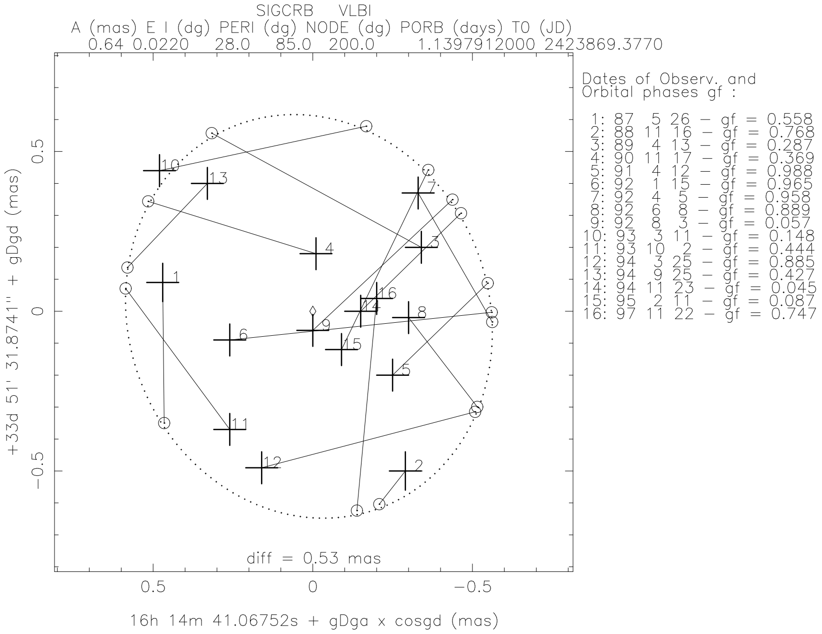

FIGURE 5. VLBI residual positions of σ^2 CrB plotted on the sky and the relative orbit of the binary superimposed. The node has been fixed to 200° to minimise the differences between the residual and calculated positions

3.4. σ^2 CrB

The RS CVn binary σ^2 CrB is made of two main sequence stars (F6 and G0) with a very short orbital period of 1.14 days. This binary has been observed at 15 epochs between 1987 and 1997, mostly in support of Hipparcos, and the residual positions after adjustment of the astrometric parameters are displayed on the sky in Figure 5 with the projected relative orbit of the binary. It is striking that these residuals are all within the orbit indicating that the radio emitting region is in the intra-stellar region of the binary. These astrometric observations suggest that the model of interconnecting loops proposed by Simon et al (1980) and Uchida & Sakurai (1983) might be responsible for the magnetic structure of this active close binary. The activity of σ^2 CrB is relatively "calm" compared to other RS CVn's, varying between a flux density of ~ 2 and ~ 30 milliJansky. This suggests a relatively stable magnetic structure connecting the two stars and steady injection of non-thermal electrons. We are analysing new VLBA data to assess if the radio centroid is positionally stable enough relative to the mass center of the system to search for possible wobble caused by an orbiting Jupiter mass companion.

3.5. HR1099 & IM Peg

In support of the NASA Gravity Probe B mission, a VLBI campaign has been undertaken on the RS CVn binaries HR1099 and IM Peg. Both of these objects have shown radio structure with double lobe at some of the epochs of observations (Ransom et al 2000a,b).

4. Conclusion

High-angular resolution maps of active binary by the VLBI technique have provided an insight of their magnetic structure. Double lobe radio structure at some epochs at least are common to the five different systems mapped by VLBI so far. The cleanest interpretation so far is for Algol and UV Ceti B for which all the orbital elements including the node axis are known. The double lobe structure suggests the existence of a dipolar magnetic field to first order aligned with the rotation axis of the active star. The radio emitting regions are above the polar caps. The VLBA circular polarisation map helps greatly for the interpretation as shown by Mutel et al (1998) for Algol. Energetic electrons expelled by the companion of the active star may be channelled to its magnetic poles where they radiate similarly to solar wind particles trapped by the magnetic field of planets in the solar system.

Astrometric VLBI observations are useful in support of the space mission Hipparcos and Gravity Probe B. They also provide an insight to better identify the radio emitting region in these systems and also has the potential to sense close unseen companion orbiting around them. The Very Low Mass star orbiting around the star AB Dor found by VLBI astrometry (Guirado et al 1997) is a very good illustration.

Circular polarisation mapping possible with the modern VLBI arrays offer great promise to improve our knowledge of the "extreme" magnetic structure that has developed in active binaries.

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