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First VLBI images of a main-sequence star

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Abstract. The binary system UV Cet A and B has been observed with the VLBA/VLA at 3.6 cm wavelength. Both dMe stars have been detected. The stronger, steady radio emitter of the two, UV Cet B, is resolved into at least two spatial components. Their relative intensities change during the 6.3 hours of observing time. One of the components is more stable and resolved, the other is possibly unresolved. The resolved component has a half-power diameter of 2.4×10^{10}cm, exceeding the size of the stellar photosphere. The separation of the two components of UV Cet B is $4.4(\pm 0.4) \times 10^{10}$cm or 4 - 5 stellar radii. The alignment of the two components is along the axis of the binary orbit and thus parallel and very likely close to the stellar rotation axis. The apparent trapping of the gyrosynchrotron emitting energetic electrons requires large coronal loops extending to several stellar radii. At the more variable source a magnetic field between 15 and 130 G is derived.

Key words: stars: individual: UV Cet – binaries: visual – stars: imaging – stars: coronae – stars: magnetic fields – radio continuum: stars

1. Introduction

The coronae of active, rapidly rotating, young stars emit several orders of magnitude more radiation than the solar corona. They have first been discovered in soft X-rays (Catura et al. 1975; Mewe et al. 1975), emitted by thermal bremsstrahlung. The even more surprising detection of quiescent radio emission (Gary & Linsky 1981) has revealed another ubiquitous constituent of such coronae: mildly relativistic electrons radiating gyrosynchrotron emission. These electrons are generally assumed to be the tail of an energetically important non-thermal population. The thermal and non-thermal emissions correlate in main-sequence dMe stars (Güdel et al. 1993) and thus appear to be causally related. The similarity to solar flares (Benz & Güdel 1994) makes it conceivable that the energy to heat the thermal corona is drawn from the non-thermal particle population. It has remained a mystery how the two particle populations can coexist in a corona since intense interaction with the thermal population would slow down rapidly the fast electrons.

Both coronal constituents are highly conductive. Thus the sources are expected to be shaped by the coronal magnetic field. Images of the radio emission thus indicate the shape and extent of closed magnetic field lines forming the stellar corona.

The extent of stellar magnetospheres is an important parameter of stellar evolution. On the main sequence, coronae are the sources of a high-speed stellar wind that carries away angular momentum depending on the strength and shape of the coronal magnetic field. The radio emission of stellar coronae has also received interest for astrometric purposes (e.g. Lestrade et al. 1994).

Very long baseline interferometry (VLBI) has recently opened the possibility for spatially resolved investigations of stellar coronae. Previous VLBI observations have measured the size at 18 cm wavelength of the dMe close-binary YY Gem (Alef et al. 1997) to be 2.0×10^{11}cm. The upper limit size of YZ CMi, $< 8.7 \times 10^{10}$cm, reported by Benz & Alef (1991) and of EQ Peg, $< 4.9 \times 10^{10}$cm (Benz et al. 1995), refer to highly polarized emission and probably a different, namely coherent radiation mechanism. Upper limits derived by Benz et al. (1995) of $< 8.1 \times 10^{10}$cm and $< 1.5 \times 10^{11}$cm for AD Leo in quiescence are more relevant for this work.

Here the first observation of a dMe star with the new Very Large Baseline Array (VLBA) is presented. The observing wavelength was 3.6 cm, increasing the angular resolution by a factor of five over the previous measurements.

2. Observations

The observations were carried out on February 4/5, 1996, at 8.413 GHz, using 10 VLBA antennas and the Very Large Array (VLA) in both phased array and interferometric modes. The VLA was in CnB configuration. The combined VLBA/VLA network had a FWHP beam size of 1.8×0.7 milliarcseconds (mas) with a position angle of -3.4° using uniform weighting. The antennas were pointed at UV Cet B, but UV Cet A then

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separated by 1.″42 was well in the beam of the VLBA. Even the phased VLA, where the A star was slightly beyond the half-power point, was usable for UV Cet A after the appropriate correction. The observing time was spread over 6.3 hours and included calibrations and 2.4 hours on the source.

Delay, delay rate and phase have been solved for the calibration source 0123-169 at an angular distance of 1.9° observed every 5 minutes. The calibrator solutions have been used to estimate the target source delays (delay-rate referencing, cf. Beasley & Conway 1995).

UV Cet (L726-8 A and B, Gliese 65 A and B) is a binary system of two main-sequence dM5.5e stars in elliptical orbit (e = 0.62) with a major axis of 7.9×10^{13}cm and an orbital period of 26.52 yr (Geyer et al. 1988). Thus the system is well separated, and the appearance of the coronae is not expected to be noticeably influenced by mass exchange. Hale (1994) has found that binary systems with a separation less than 10 AU have coplanar orbital and equatorial planes within an angle of less than 10°. Thus it is assumed in the following t hat the rotation axis of UV Cet B is approximately parallel to the well known orbital axis of the binary system.

The photospheric radii of the stars is estimated to be $1.0{\times}10^{10}$cm (0.25mas, Pettersen 1980). The system is at a distance of 2.695($\pm$0.03) pc. The parallax produces an apparent motion of 0.138 mas/h mostly in declination. The proper motion is 0.379 mas/h predominantly in right ascension. The reported space velocity make UV Cet a likely member of the Hyades supercluster (Jeffries & Jewell 1993), suggesting an approximate age of 6×10^8 yr, still relatively close to zero main-sequence age.

UV Cet is a well-known radio source and was among the first dMe stars discovered at radio wavelengths (Gary and Linsky 1981). At 3.6 cm it typically has a flux of 1 mJy (e.g. Güdel & Benz 1996). In the observations of February 4/5, 1996, the quiescent flux was at an elevated level of 8.5 mJy on average.

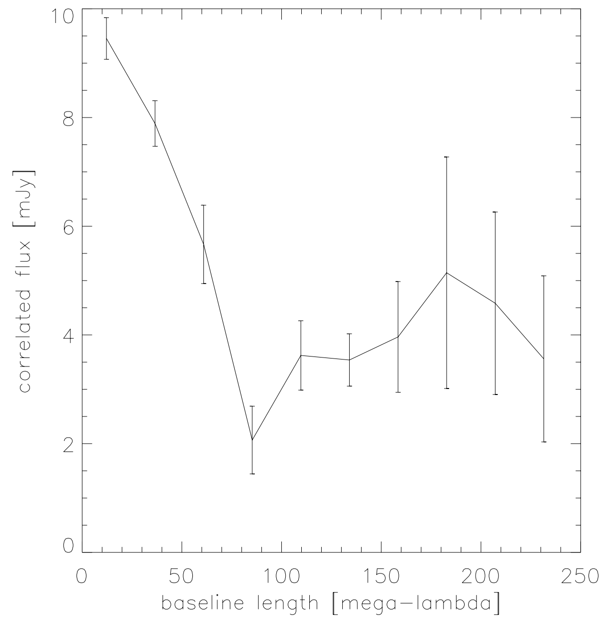

Fig. 1. The correlated flux of UV Cet B is shown vs. interferometric baseline length in units of one million wavelengths (3.6 cm). The values are averaged over all baselines of VLBA/VLA and time intervals from 22:40 to 23:25 UT.

3. Results

Fig. 1 summarizes the interferometer results. The correlated flux of all baselines has been averaged in bins of baseline length. The general decline with baseline length clearly indicates that the source is spatially resolved. Note that the error bars do not only include noise, but possibly also image structure causing variations of the correlated flux with time.

The minimum at about 80 Mλ could in principle be due to either a single sharp edged intensity distribution (single disk or ring) or due to the beating between two components. Our data strongly favour the second interpretation, based on the fact that the closure phases – although very noisy – are all consistent with $\pm$90°, and the fact that the fall-off of amplitude versus projected uv distance is azimuth dependent in the uv plane. For a disk or ring model we would instead expect some closure phases to be around 180°, since in that case the structure phase on baselines beyond 80 Mλ where the amplitude increases with uv distance would be 180°. It would also be difficult to obtain the observed azimuth dependence of amplitude versus projected uv distance with such a model. Given a two component model, the lower amplitude peak at 180 Mλ compared to the peak at 0 Mλ suggests that at least one of them is resolved. We have thus modeled the data with two sources in hourly bins. The model fitting was iterated with self-calibration of individual scans of 2.5 minutes duration, during which the S/N ratio on nearly all closure triangles was significantly greater than unity. This procedure has the advantage that the proper motion and parallax motion of the star are eliminated. The procedure was performed for hourly bins with the following results:

The resolved source, to be referred to as source 1, is relatively constant in flux except for the first hour when the flux rises (Fig. 2). A gaussian shape produces smaller χ^2-values than a disk, hence gaussians were used for both sources. The half-power diameter of source 1 is on the average 2.4×10^{10}cm (0.59 mas) and is relatively stable during the observing time.

Source 2 strongly declines after a peak at 23:00 UT. The distance and position angle relative to source 1 are on the average 1.08$\pm$0.1 mas (4.4×10^{10}cm) and 62°, respectively. The source appears to be stationary. The alignment of the two sources is close to the projected angle of the orbital axis of 60.°2 and therefore to the rotational axis of the star. After 01:00 UT the position is not reliable since the flux of source 2 becomes weak and the star sets at the two most easterly VLBA telescopes. The algorithm finds a best fitting half-power diameter of 0.3 mas (1.2×10^{10}cm) at peak flux. This is only 0.42 of the beam minor axis, thus the source is not truly resolved.

Fig. 2. The results of the model fits in hourly bins for two sources are presented vs. time. The total flux densities in both polarizations are added and plotted for each source (solid curves). The diameter of the resolved source 1 (*dashed*) is in milliarcsec (1 mas corresponds to 4.03×10^{10}cm). The position angle (radians) of the unresolved source 2 relative to source 1 is shown *dotted*, and the angular distance (mas) between the two components is *dash-dotted*.

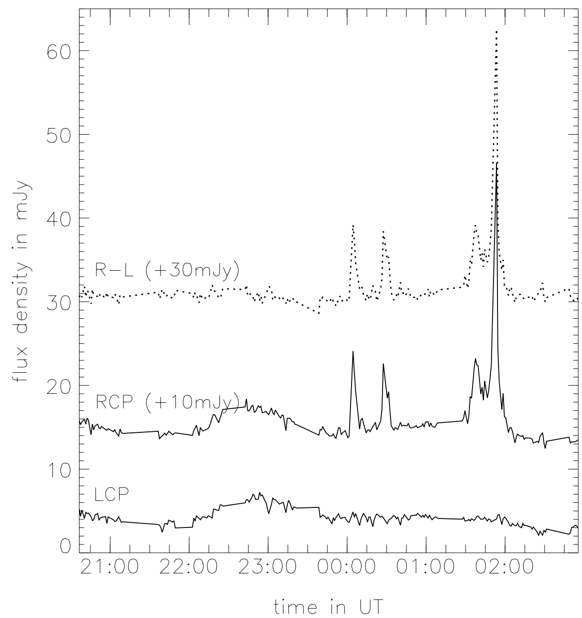

Fig. 3. Time profile of total radio emission of the combined system UV Cet A and B as observed with the VLA alone in interferometric mode. The integration time is 60 s. The Stokes V parameter is shown *dotted* (R-L, shifted by +30 mJy), as well as the right and left circular modes of polarization.

The brightness temperature is defined according to the Rayleigh-Jeans relation for unpolarized radiation

$$T_b \ := \ \frac{2c^2 F D^2}{\pi k_B \nu^2 d^2} \ , \qquad (1)$$

where F is the total flux density, D the distance, and d the source diameter. For UV Cet and these observations,

$$T_b \ \approx \ 2.5 \times 10^7 \ \frac{F_{mJy}}{d^2_{mas}} \ \ [\mathrm{K}]. \qquad (2)$$

The values for the brightness temperature of source 1 scatter between 1.8×10^8 and 5.7×10^8K. The formal radius derived for source 2 yields a temperature of 2×10^9K.

The sum of the fluxes of source 1 and 2 has a peak at 23:00 UT. This enhancement is clearly visible in the VLA data (R+L in Fig.3), indicating consistency. Its polarization is 10% right circular and compatible with gyrosynchrotron emission. Fig. 2 suggests that the peak is caused by a gradual flare at source 2 having a duration of about 2 hours.

Fig. 4 gives an impression of the appearance of UV Cet B at 3.6 cm. The image is the result of iterative self-calibration and model fitting of individual 2.5 minute scans. The integration time totals 20.0 minutes of on-source observations. Proper motion and parallax motion are eliminated by self-calibration. The image was restored with a circular beam of 0.8 mas diameter. Source 2 (left) is in its peak flare state. Source 1 (right) is more extended and weaker in the particular interval shown.

The optical position of the star was not observed by the Hipparcos satellite and remains uncertain to within 50 mas (Gliese & Jahreiss 1979). The error box includes the area presented in Fig.4.

UV Cet A

Fig. 3 also shows extremely strong and fully right circularly polarized flares. The VLA data clearly show that they originate from the other star, UV Cet A. This is confirmed by the VLBA, finding the star at a right ascension of 01^h 39^m 00.^{s}60863 and a declination of -17° 57' 04.''5913 (J2000.0, epoch 1996.0958). The upper limit diameter (3σ) of the largest flare is 1.9×10^{10}cm (0.47 mas), indicating an unresolved source with a brightness temperature exceeding 1.2×10^{10}K. Both polarization and brightness temperature strongly suggest the operation of a coherent radiation mechanism.

4. Discussion

The unpolarized emission is generally attributed to gyrosynchrotron radiation. The magnetic field can be estimated from the observed intensity and the assumption of a stable source, requiring that the particle pressure is less than the pressure of the magnetic field, thus

$$n_e < \varepsilon > \ \leq \ \frac{B^2}{8\pi} \ . \qquad (3)$$

where n_e is the density of non-thermal electrons and ε the kinetic electron energy. Assuming a power-law distribution of particle energies with an exponent δ, the average energy $< \varepsilon >= (\delta -$

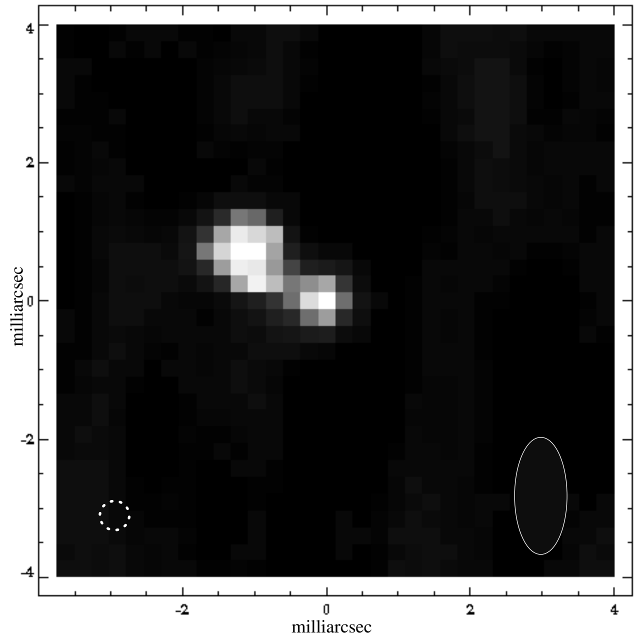

Fig. 4. Cleaned map of UV Cet B for February 4, 1996, 22:30 - 23:25 UT, observed with the VLBA/VLA at 3.6cm. The observing beam size is shown in the lower right corner. The map center is at RA: $01^h\ 39^m\ 00.^s54890$ and Dec: $-17°57'03.''4560$ (J2000.0). For size comparison, the photospheric radius is indicated by a dashed circle in the lower left corner. The properties of source 1 (right) and source 2 (left) are described in the text.

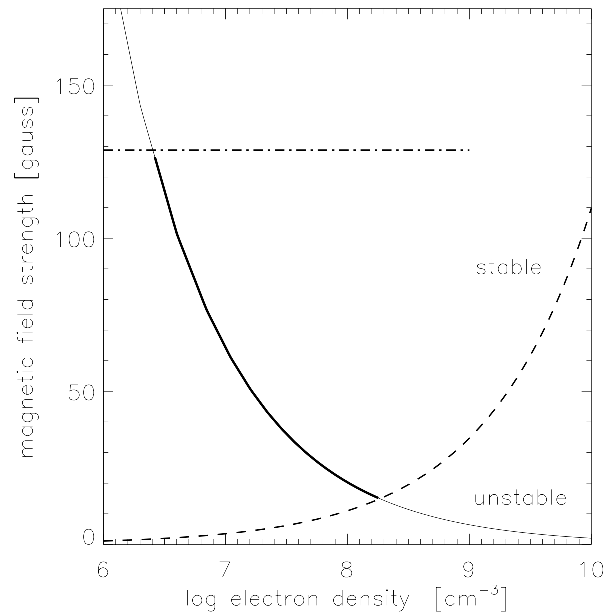

Fig. 5. The relation (7) between the magnetic field B in source 2 and the density n_e of energetic electrons is presented by the *solid* curve. The *dashed* curve shows the lower limit of B according to Eq.(3). The allowed part of Eq.(7) is shown *bold*. The *dash-dotted* line represents the value given by Eq.(10).

$1)/(\delta - 2)\varepsilon_0$, where ε_0 is the low-energy cutoff of the energy distribution.

For mildly relativistic electrons yielding gyrosynchrotron emission, Dulk and Marsh (1982) have presented simplified expressions of the emissivity η. An isotropic pitch angle distribution is assumed. For x-mode (where more of the radiation originates), a power-law exponent in the range $2 \lesssim \delta \lesssim 7$, $\theta \gtrsim 20°$ and $\omega/\Omega_e \gtrsim 10$, they derive

$$\eta(\omega,\theta) \approx 3.3 \times 10^{-24} B \;\; n_e(>10\text{keV}) \;\; 10^{-0.52\delta} \times (\sin\theta)^{-0.43+0.65\delta} \left(\frac{\omega}{\Omega_e}\right)^{1.22-0.90\delta} [\text{erg s}^{-1}\ \text{cm}^{-3}\text{Hz}^{-1}\ \text{sterad}^{-1}] \quad . \qquad (4)$$

θ denotes the emission angle to the magnetic field B [G], $\Omega_e = eB/m_e c$, and n_e is in cm^{-3}. A power-law cutoff at $\varepsilon_0 = 10$ keV has been assumed in the numerical constant in Eq. (4). If it is at a different but non-relativistic energy, the virtual number density $n_e(>10\text{keV}) := n_e(>\varepsilon_0)\ (\varepsilon_0/10)^{\delta-1}$ must be used. Since electrons at 10 keV contribute little to gyrosynchrotron emission, the cutoff value is not relevant.

Eq.(4) can be reduced by putting in the gyrofrequency Ω_e, using $\theta \approx \pi/2$, where the emission is most efficient, and $\delta \approx 2.5$ as observed in the quiescent emission of this star (Güdel et al. 1998). The intensity for optically thin emission is given by

$$I \;\; \approx \;\; 1.8\,\eta\, d \;\; , \qquad (5)$$

assuming that the o-mode has a similar emissivity in agreement with the observed low polarization. Observations 2 yield

$$I \;\; = \;\; 3.9 \times 10^{-8}\ \text{erg s}^{-1}\ \text{cm}^{-2}\text{Hz}^{-1}\ \text{sterad}^{-1} \qquad (6)$$

in source 2 at 23:00 UT. The formal value of the source diameter was used in Eq.(6). If the actual diameter were less, the value would be a lower limit. Eqs.(4) - (6) are combined to

$$B \;\; \approx \;\; 2.03 \times 10^5 \frac{1}{\sqrt{n}} \quad . \qquad (7)$$

The two conditions are displayed in Fig. 5. Note that the limit of Eq.(3) depends linearly on the assumed ε_0 and is subject to considerable uncertainty. If the diameter of source 2 is less than the formal value, Eq.(7) gives a lower limit on B. According to Fig. 5, the source density n_e has an upper bound of about $1.9 \times 10^8 \text{cm}^{-3}$, corresponding to a lower limit on B of about 15 G. The resulting source parameters are consistent with the assumption of optically thin emission.

The decay of the flaring source 2 may have several reasons. Assuming that the decay is caused by just synchrotron radiation losses of electrons with Lorentz factors γ,

$$\dot{\gamma} \;\; = \;\; -1.3 \times 10^{-9} B^2 \gamma^2 \quad [\text{s}^{-1}], \qquad (8)$$

the observed decay time can be used for an independent upper limit on B: The average frequency of synchrotron emission is

$$< \nu > \; = \;\; 1.3 \times 10^6 B \gamma^2\ [\text{Hz}] \qquad (9)$$

(from Melrose 1980). Approximating the observing frequency by $\nu \approx <\nu>$, Eqs.(8) and (9) yield the decay time

$$\tau = \frac{\gamma}{|\dot{\gamma}|} \approx 9.57 \times 10^6 B^{-3/2} \quad [\mathrm{s}]. \tag{10}$$

The observed value is τ=6550 s (cf. Fig.2), and Eq.(10) then yields $B \approx 129$ G. The field strength is less if there are other energy losses. According to Eq.(9), the Lorentz factor of the electrons emitting at ν is near 7.1, which is a lower limit.

The magnetic field may be modeled by a dipole field

$$B \approx B_0 \left(\frac{R_0}{R}\right)^3 , \tag{11}$$

where B_0 and R_0 are a reference field and radius, respectively. If R_0 is about the stellar radius and B_0 a few thousand gauss, the required field strength can barely be met at 4.4 stellar radii (4.4×10^{10}cm). More likely, however, the dipolar radius is smaller than a stellar radius, and the field drops off faster. It suggests that the star is located between the two components, reducing the height of the sources by up to a factor of two.

5. Summary

First VLBI images show a astonishingly large and structured appearance of the corona of the young main-sequence star UV Cet B. Its total extent is 5.6×10^{10}cm (1.4 mas). The centroids of the two observed components are separated by 4.4 stellar radii. The two components of the stellar image are approximately aligned with the stellar rotation axis. The relative stability of the observed components suggest stable magnetic loops extending to more than 2.2 and possibly 4 stellar radii with loop top field strengths exceeding 15 G. The large separation makes it difficult to identify the more stable component with the star, but rather suggests that the stellar center of mass is located in between the two components. In any case, the magnetosphere is much more extended in proportion than the largest stable solar loops that reach only about $1.4R_\odot$ and extend farthest near the equator. The corona of this fully convective young star appears to have a very different sh ape than the Sun's corona.

Future observations may be able to detect the stellar rotation. It has not been noticed during the 3.5 hours of high sensitivity and remains unknown. Such observations may give a stereoscopic view and identify the center of mass. Nevertheless, it is clear that the extended, structured corona may put severe limits on astrometric studies of active, late-type stars.

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