Astron. Astrophys. 317, 707–711 (1997)

ASTRONOMY AND ASTROPHYSICS

VLBI measurement of the size of dMe stars

W. Alef[1], **A. O. Benz**[2], **and M. Güdel**[3]

[1] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany (walef@mpifr-bonn.mpg.de)
[2] Institute of Astronomy, ETH-Zentrum, CH-8092 Zürich, Switzerland (benz@astro.phys.ethz.ch)
[3] Paul-Scherrer-Institute, CH-5232 Villigen, Switzerland (guedel@astro.phys.ethz.ch)

Received 2 January 1996 / Accepted 13 June 1996

Abstract. The binary system YY Gem, which consists of two dM1e stars, has been observed during an eclipse using intercontinental Very Long Baseline Interferometry (VLBI) at 1.6 GHz. The stellar emission was at a low, quiescent level at all observing periods. The correlated flux decreases slightly with baseline length, indicating that the source is resolved at the longest baselines. This is confirmed by model fits, which give a FWHM size of 0.94($\pm$0.24) mas ($2.0 \cdot 10^{11}$cm or 2.1 photospheric diameters) for the radio emitting source. A lower limit to the size derived from the lack of observable eclipse effects is consistent with this value. The resulting brightness temperature of $1.1 \cdot 10^9$ K is compatible with gyrosynchrotron emission. Deviations from circular symmetry are not significant. The loops that trap the radio emitting electrons reaching an altitude of probably more than a stellar radius appear to be distributed isotropically within the limits of the resolution.

Key words: stars: coronae – binaries: eclipsing – YY Gem – radio continuum: stars

1. Introduction

The radio emission from active stellar coronae is generally believed to originate in closed magnetic loops, and its investigation may yield information on the structure and size of stellar coronae. Quiescent radio emission has been detected from rapidly rotating main-sequence stars from class M6 to F0 (Güdel et al. 1995). There are at least three emission mechanisms (for a review see Güdel 1994): (i) Most common seems to be gyrosynchrotron emission with its characteristic spectrum decreasing at high-frequencies and with a low degree of circular polarization. (ii) At frequencies above 10 GHz, thermal ($\sim 10^7$ K) gyroresonance emission may occasionally occur, recognizable from its ν^2 increasing spectrum, suggesting coronal magnetic fields of 1 to 2 kgauss (Güdel & Benz 1989; White et al. 1994). (iii) Coherent emission processes are generally believed to be responsible for the occasionally observed emission with degrees of circular polarization up to 90% and narrow spectral structures (Lang & Willson 1986, 1988; Benz & Alef 1991; Benz et al. 1995).

If confirmed, gyrosynchrotron emission must be taken as evidence for a surprisingly large and persistent population of mildly relativistic electrons unknown from the Sun. Detailed calculations and models find low-polarization emission in the 3 – 8 GHz range consistent with optically thin emission (e.g. Kundu et al. 1987; Güdel & Benz 1989; White et al. 1989).

Previous VLBI observations of nearby single main-sequence stars have not resolved the radio sources. The dMe star YZ CMi was detected at 1.7 GHz, with an upper limit to its size of 10^{11} cm or 3.4 photospheric diameters (Benz & Alef 1991). The quiescent emission of a similar star, AD Leo, was found to originate within less than $1.5 \cdot 10^{11}$ cm or 3.7 photospheric diameters (Benz et al. 1995). In both cases the circular polarization was high: $>$ 80% and 50%, respectively. The lower limits on the brightness temperature were $4 \cdot 10^8$ K and $2.2 \cdot 10^9$ K, respectively. It has been suggested that coherent emission processes are responsible in these stars. Note that such processes have no stringent upper limit on the brightness temperature and thus no lower limit of the source size.

Here we present results from VLBI observations of a well-known source of gyrosynchrotron emission, YY Gem (= Gl 278 C), with the aim of testing coronal models with observed sizes. YY Gem is the most suitable eclipsing binary system of dwarf M stars. The two components are nearly identical dM1e stars in an essentially circular orbit ($e \leq$0.01, Bopp 1974) viewed almost edge-on ($i = 86.^\circ4 \pm 0.^\circ1$, Kron 1952). YY Gem is at a distance of only 13.89 pc and has a joint apparent magnitude $m_v = 9.07$ and $R - I = 0.78$. The two stars have a maximum separation of $2.687 \cdot 10^{11}$ cm (= 1.293 mas). The rotation of the two stars is locked to the orbital period of 19.54277 hours (Bopp 1974). In spite of the closeness of the two stars, the YY Gem pair is not atypical in its level of activity. The two similar eclipses per orbit with an occultation depth of about 0.55 mag in visual light are consistent with the primary and secondary stars having diameters of $9.19(\pm 0.28) \cdot 10^{10}$ cm (= 0.44 mas) and $8.08(\pm 0.28) \cdot 10^{10}$ cm (= 0.39 mas), respectively (Leung & Schneider 1978). Their masses are $0.62 \pm 0.03 M_\odot$ and $0.58 \pm 0.03 M_\odot$. The geometry is shown in Fig. 1.

Send offprint requests to: W. Alef

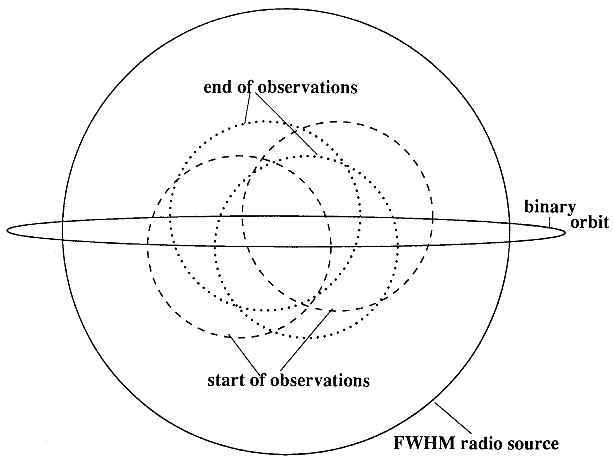

Fig. 1. Schematic drawing of the geometry of the eclipsing binary system YY Gem. Solid circle: full width at half maximum (FWHM) of radio source (best fit) at 1.6 GHz. Solid ellipse: projected binary orbit. Dashed circles: photospheric disks at start of VLBI observations. Dotted circles: photospheric disks at end of VLBI observations.

As a member of the Castor Sextet, YY Gem must be relatively young. Chabrier & Baraffe (1995) estimate its age to be 10^8y from model calculations of the interior, suggesting that the two stars are in the late pre-main-sequence contraction phase. Their metallicity is likely to be oversolar and the radiative core extends to 70% of the radius.

The radio emission of YY Gem was first discovered by Linsky & Gary (1983). Subsequent multi-frequency observations by Gary (1985) and White et al. (1993) have not revealed evidence for gyroresonance or coherent emissions and are consistent with the gyrosynchrotron mechanism. Gary (1985) observed YY Gem for 3/4 of a rotation period and noticed flux variations, which he attributed to rotational modulation. A small decrease at the time of the primary eclipse (phase 0, secondary in front of primary) was confirmed later (Gary 1990, private communication).

The YY Gem pair has also been detected as a quiescent source of X-rays (Caillault 1982). Haisch et al. (1990) noted a pronounced X-ray eclipse of the order of 50% for zero phase, similar to visual eclipses. This suggests that the thermal coronal plasma does not extend much in height compared to a stellar radius and is evenly distributed over the stellar surfaces. A similar distribution has been found by the same authors from much more data of the Mg II line emission in UV showing no concentration near the surface points of closest distance. Since Mg II line emission originates from the active chromosphere, this suggests that a large fraction of the two surfaces are covered with plage regions.

There are controversial reports concerning the flare distribution in longitude. Bopp (1974) reports a random distribution for both flares and active regions over the stellar surfaces. Doyle & Mathioudakis (1990), however, find an order of magnitude more flare energy outside of eclipses, suggesting that more energy is released between the two components.

YY Gem is a BY Dra-type system defined as exhibiting rotational modulation of the optical light curve by spots. The number, size and distribution of spots has been modeled by Hatzes (1995) from Doppler images. Since many solutions can be found which fit the data, simplifying assumptions have to be made, selecting against complex structures. Hatzes (1995) finds on both stars spot regions in a band of latitude centered at 45° North, and only a weak equatorial spot in component A between phase 0.16 and 0.5. There is no high-latitude spot nor a pronounced region near the points of closest distance between the stars. Doppler imaging suggests a number of 4–6 spots per star. The absence of polarization in Zeeman splitting of optical lines and the lack of circular polarization in the quiescent radio emission are consistent with this distribution of the magnetic flux being neither concentrated in a global dipole field, nor in very few spots. The observations thus suggest that the YY Gem stars have many extended star spot regions.

2. Observations

The YY Gem system was observed on 1990 March 15/16, and 1991 September 26 and 28 using intercontinental VLBI at 1.6 GHz (18 cm). The instrumental setup included the telescopes in Arecibo (Puerto Rico) (⊘ 305 m), Effelsberg (Germany) (⊘ 100 m), the Very Large Array (VLA, New Mexico, USA) (⊘ 27 × 25 m), the 76m "Lovell" telescope at Jodrell Bank (UK), the Green Bank 140 foot (West Virginia, USA), and the 40m Owens Valley dish (California, USA). We used the Mark III recording system in Mode A with a bandwidth of 28 MHz in both left and right circular polarization. The data were correlated on the MK3 correlator of the MPIfR, Bonn, and fringe fitted in AIPS.

The data were calibrated using measured system temperatures and antenna gain curves. We have checked the consistency of the amplitude calibration with a scan on the amplitude calibration source OJ287 in both hands of polarization separately. Gain corrections of up to 12% were necessary, calculated with the assumption of zero circular polarization for OJ287. We estimate the flux calibration error to be less than a few percent.

The VLA was available in phased array mode for VLBI producing a pencil beam of 1.2 arcsecond width, as well as in its synthesis mode as an imaging interferometer in configuration A. We made use of the latter for a short baseline reference. The VLA interferometer data were flux calibrated using 3C48. For phase calibration, for the VLA we used the same sources as for the VLBI network. The VLA data were edited, calibrated, and mapped using standard AIPS procedures. The maps were cleaned before reading the flux values of YY Gem to remove the sidelobes of field sources. On all three days the VLA suffered terrestrial interference which seems to have affected the imaging, but not the VLBI. After considerable editing, the average total flux measured with the VLA was practically constant at 1.53 ± 0.25 mJy on 1990 March 15/16 with no detectable polarization, and of the order of 0.3 ± 0.1 mJy on 1991 September 26 and 28, again with no strong polarization.

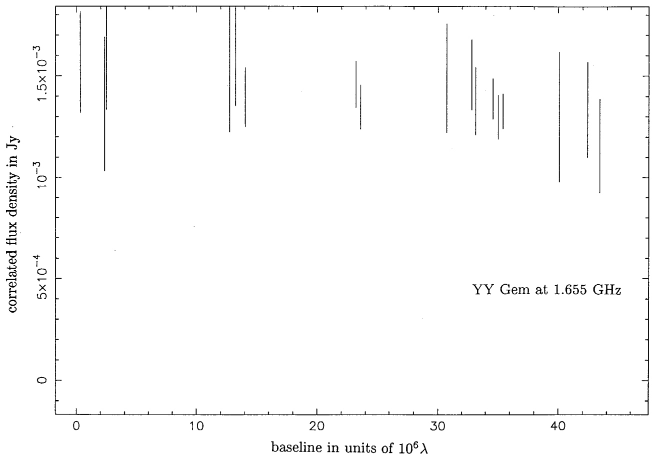

Fig. 2. Correlated VLBI and VLA flux densities of YY Gem. All the scans have been averaged and the observations in left and right hand circular polarizations are added.

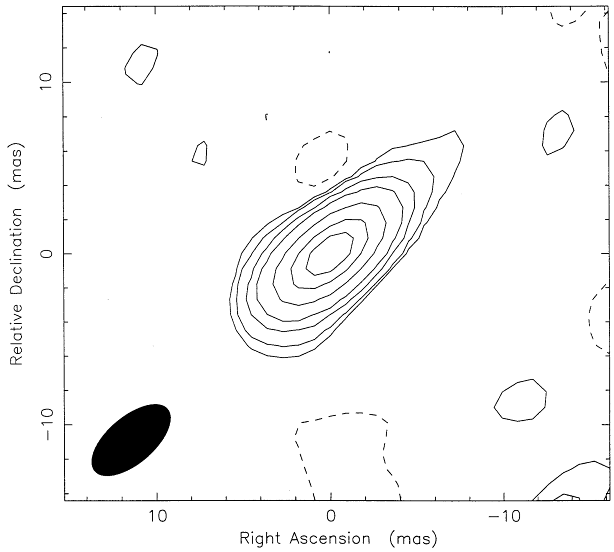

Fig. 3. VLBI clean map of YY Gem at 1.6 GHz. The restoring beam (natural) is shown in the lower left corner. The contour levels are a -1, 1, 2, 5, 10, 25, 50, and 75% of the peak at 1.35 mJy.

We observed very clear VLBI fringes on the first date over a long period and on nearly all baselines (except for Green Bank to Jodrell Bank and all baselines to Owens Valley which had technical problems). The resulting natural beam size is 5.5 mas $\times$ 2.7 mas. In the course of these observations the YY Gem system underwent a primary eclipse.

The source was not detected on 1991 September 26 at the most sensitive VLBI baselines. In the following only the results from the first period are presented.

3. Results

Fig. 2 shows the correlated flux densities on VLBI baselines and at the VLA. The VLA value at $0.2 \cdot 10^6\lambda$ has a low accuracy due to deleting disturbed visibilities at short VLA baselines. The smooth dependence of correlated flux on baseline length with only a small decrease in amplitude on the longest baselines suggests a simple and only slightly resolved source structure.

The closure phases from 13-minute scans have been calculated on all triangles of sufficient sensitivity. None of the ten values was found to be significantly different from zero. Therefore no deviation from symmetry has been detected in the source.

A cleaned map of the source is presented in Fig. 3. Its dynamic range is about 1:70. The FWHM restoring beam shown corresponds to the effective spatial resolution. A slight S.E. extension in Fig. 3 is marginally significant at the 5σ contour level.

Gaussian models have been fitted independently to the data in left and right hand circular polarization. For both modes the acceptable fits have FWHM sizes in the range of 0.8 to 1.3 mas. The best fit is for a source diameter of 1.05 mas. The models are compatible with a circularly symmetric source. Models with less than 0.6 mas FWHM show definitely poorer results of the χ^2-test. The indication of a finite width seems to be robust and has appeared in all the different ways of data reduction applied and discribed below.

Additionally, we have used the Caltech DIFMAP program (Shepherd et al. 1994) on the summed left and right circular polarization data, yielding a best fitting model of 1.18×0.8 mas in position angle $-82°$ or if only circular models were allowed of 0.94 mas. The difference between the two DIFMAP models is not statistically significant; the reduced chi-squared for both fits is 0.47 and 0.45 respectively.

The AIPS routine UVFIT fits a gaussian (assumed symmetric) with a FWHM of 0.94 ± 0.24 mas. If the error distribution is gaussian, the source was thus resolved at the 4σ level of significance. On this proviso, it is the first time the radio emission of a dMe star has been resolved.

These consistent results and relatively small standard deviations of the fits are only possible due to the relatively high signal to noise ratio of this experiment. Thus we conclude that the most likely FWHM size of YY Gem at 1.6 GHz is 0.94 ± 0.24 mas, corresponding to $2.0(\pm0.5) \cdot 10^{11}$cm or 2.1 ± 0.6 photospheric diameters. The source is schematically shown in Fig. 1 in relation to the orbit and the visual diameters of the stars.

The resulting brightness temperature of YY Gem is $5.7 - -15 \cdot 10^8$ K, the best estimate being $1.1 \cdot 10^9$ K. The range of values is acceptable for the proposed gyrosynchrotron mechanism. It is similar to values derived from VLBI observations of RS CVn systems and post T Tauri stars (Mutel et al. 1985; Phillips et al. 1991).

Model fits to the intensity in left and right hand circular polarization yield the time integrated flux density in the two modes. The values were equal within the errors, so we have estimated the upper limit of polarization from the 3σ accuracy of the values. This yields a degree of circular polarization less than 8%, consistent with gyrosynchrotron emission.

Fig. 4 displays the temporal variation of the flux density of YY Gem with a time resolution of the 13-minute VLBI scans. There is no significant variation in time on any of the baselines.

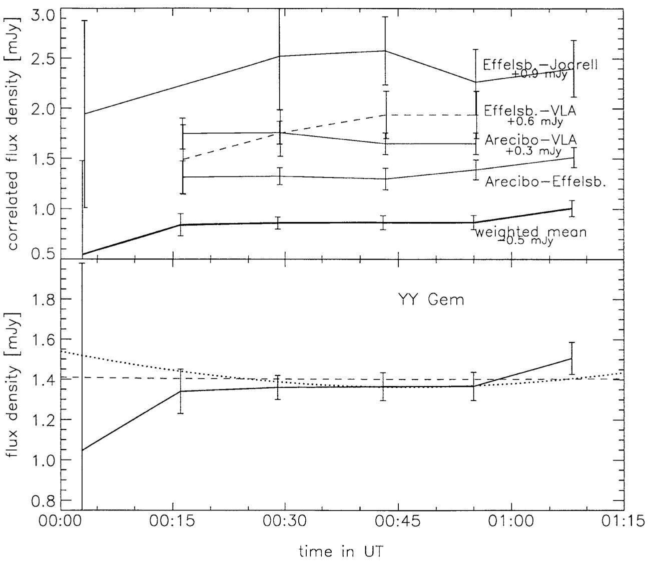

Fig. 4. *Top*: Correlated flux density vs. time as derived from the VLBI observation at 1.6 GHz. Four sensitive baselines and their weighted mean are shown. The flux densities for the various baselines are offset for clarity by the amounts indicated in the figure. *Bottom*: The weighted mean (solid) is compared with simulations of the occultation of a radio source having a source diameter of the VLBI value of 0.94 mas (dashed) and the lower limit value of 0.43 mas (dotted) for each star (half occultation).

In particular, we note that in Fig. 4 there is no decrease in flux during the eclipse. This contradicts previous claims which may have been based on higher frequency observations.

Is the absence of a radio eclipse consistent with the most likely observed diameter of the radio source? Let us assume a symmetric, gaussian model for the source intensity,

$$I(x,y) = I_0 \exp(-\frac{x^2+y^2}{\sigma^2}) , \tag{1}$$

where x and y are coordinates in the plane of the sky and $\sigma = 0.631$ mas as observed. Assuming all the emission is occulted, the flux density at a full eclipse would be

$$F_{ec} = \int_{R_B}^{\infty} I(x,y)\mathrm{d}x\mathrm{d}y = 2\pi I_0 \sigma^2 \exp(-\frac{R_B^2}{\sigma^2}) , \tag{2}$$

where R_B is the radius of the occulting disk, the visual radius of component B. Thus the flux reduction by the phase 0 eclipse is at maximum

$$\frac{\Delta F}{F} = \frac{F - F_{ec}}{F} = 0.091 . \tag{3}$$

The value derived in Eq. (3) is reduced by a factor of two if there are two equal radio sources, each associated with a star and only one is occulted (half occultation). The value is the difference from the completely unocculted flux, F. Since the radio source was occulted to some extent throughout the VLBI observation, the effective reduction is even less. It has been calculated to be 6.7% between the start of the observation and the eclipse maximum (full occultation), using the observed diameter of 0.94 mas and the geometry given by Kron (1952) and Leung & Schneider (1978) displayed in Fig. 1.

The measurement errors as can be seen in Fig. 4 are on the order of about 10% and more. Therefore the small eclipse effect would be difficult to notice. Nevertheless, the data seem to be more consistent with the smaller effect of half occultation. Associating the radio emission with component B only would predict a complete occultation during the other eclipse at phase 0.5. This can be excluded from Gary's (1985) and Haisch et al.'s (1990) observations. We will therefore assume in the following discussion that the radio source is not concentrated between the two stars, but consists of two or more sources associated with each star. This assumption needs confirmation by observations at other orbital phases of YY Gem.

The absence of an observable eclipse effect puts a lower limit on the size of the radio corona. For the observed upper limit of the eclipse effect at the level of three standard deviations, $\Delta F/F < 0.18$, the inversion of Eqs. (2) and (3) requires that the FWHM is at least 0.43 mas, assuming half occultation, and 0.62 mas for full occultation. This independently confirms the size of the YY Gem radio source as of the order suggested by VLBI.

4. Discussion and conclusions

VLBI measurements of the brightness temperature ($9 \cdot 10^8$ K) and the observed degree of circular polarization (<8%) of the dMe binary system YY Gem are consistent with the gyrosynchrotron mechanism of energetic electrons. Thus we compare the VLBI observations to corresponding geometrical models of dMe star radio emission.

Gary (1986) considered a buried magnetic dipole in E–W direction at a depth of 0.3 stellar radii having a surface field of 10 kG. A population of thermal electrons at $3 \cdot 10^8$ K with a density of 10^{-4} of the ambient corona causes the radio emission. The model produces the observed flux at 1.6 GHz and the absence of an eclipse effect at zero orbital phase, but fails on the brightness temperature. As already pointed out by Gary, a nonthermal (power-law) electron distribution may improve the agreement in flux and possibly in brightness.

White et al. (1989) have modeled the radio emission of dMe stars by several active regions consisting of buried dipoles. The depth of the dipole, for which they used 10^{10} cm, corresponds roughly to the size of the active region on the surface and the height of a typical loop in the corona. They also suggest brightness temperatures in excess of 10^9 K. The combination of many active regions at high brightness temperature is equivalent to a filling factor less than unity and is consistent with these observations. The typical loop height may be estimated as half the observed source diameter minus the visual diameter of component A, yielding 0.30 mas (= 1.37 stellar radii = $6.3 \cdot 10^{10}$ cm). The lower limit to the VLBI size requires $3.7 \cdot 10^{10}$ cm and would suggest a dipole depth of more than half a stellar radius, or more than the theoretical depth of the convection layer.

Furthermore, the observed circular symmetry of the source suggests that many such large loops coexist, making the corona to appear rather symmetric. VLBI observations with higher spatial resolution and at other wavelengths are needed to improve the significance of the size measurement of the loops and to confirm the marginally observed deviation from spherical symmetry.

Acknowledgements. We acknowledge the cooperation of the American and European VLBI networks and the correlator staff at MPIfR in Bonn. We thank Pablo de Vicente for help with the correlation and Richard Porcas for discussions and carefully reading the manuscript. We are also grateful to the Caltech VLBI group and the NRAO AIPS group for their extensive support of the project. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center which is operated by Cornell University under contract with the US National Science Foundation. The VLA is a facility of the NRAO, which is operated by the Associated Universities, Inc., under cooperative agreement with the US National Science Foundation. MG acknowledges the hospitality of the VLA AOC and the Institute of Astronomy of ETH Zürich. This work has been financially supported by the Swiss National Science Foundation (grants 20-40336.94 and 8220-033360) and NASA grant NAG5-2075 to the University of Colorado.

References

Benz A.O., Alef W., 1991, A&A 252, L19
Benz A.O., Alef W., Güdel M., 1995, A&A 298, 187
Bopp B.W., 1974, ApJ 193, 389
Caillault J.-P., 1982, AJ 87, 558
Chabrier G. & Baraffe I., 1995, ApJ 451, L29
Doyle J.G. & Mathioudakis M., 1990, A&A 227, 130
Gary D.E.,1985, in: Radio Stars, eds. R.M. Hjellming and D.M. Gibson, Reidel, Dordrecht, p. 185
Gary D.E.,1986, in: Cool Stars, Stellar Systems and the Sun, eds. M. Zeilik and D.M. Gibson, Springer, Heidelberg, p. 235
Güdel M.,1994, ApJS 90, 743
Güdel M., Benz A.O., 1989, A&A 211, L5
Güdel M., Schmitt J.H.M.M., Benz A.O., 1995, A&A 302, 775
Haisch B.M., Schmitt J.H.M.M., Rodonò & Gibson D.M., 1990, A&A 230, 419
Hatzes A.P., 1995, IAU Symp. 176 on *Stellar Surface Structure*, (ed. K.G. Strassmeier), p.90
Kron G.E., 1952, ApJ 115, 301
Kundu M.R., Jackson P.D., White S.M., Melozzi M., 1987, ApJ 312, 822
Lang K.R., Willson R.F., 1986, ApJ 302, L17
Lang K.R., Willson R.F., 1988, ApJ 326, 300
Leung K.-C. & Schneider D.P., 1978, AJ 83, 618
Linsky J.L., Gary D.E., 1983, ApJ 274, 776
Mutel R.L., Lestrade J.-F., Preston R.A., Phillips R.B.,1985, ApJ 289, 262
Phillips R.B., Lonsdale C.J., Feigelson E.D., 1991, ApJ 382, 261
Shepherd M.C., Pearson T.J., Taylor G.B., 1994, BAAS, 26, 987
White S.M., Kundu M.R., Jackson P.D., 1989, A&A 225, 112
White S.M., Lim J., Kundu M.R., 1994, ApJ 422, 293

This article was processed by the author using Springer-Verlag TEX A&A macro package version 4.