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ASTRONOMY AND ASTROPHYSICS

Radio emission from Algol-type binaries

I. Results of 1992-1993 VLA survey

G. Umana[1], **C. Trigilio**[1], **and S. Catalano**[2]

[1] Istituto di Radioastronomia del C.N.R., Stazione VLBI di Noto, C.P. 141, Noto, Italy
[2] Osservatorio Astrofisico di Catania, Viale A. Doria 6, I-95125 Catania, Italy

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Abstract. In this paper we report on a 5 GHz survey of 26 Algol-type binaries. Six systems were detected. We combine the new results with previously published data to derive some radio characteristics of Algols and to compare them with those of other active binaries. The radio detection rate of 30 %, a factor that is somewhat smaller compared to the case of RS CVn-type, does not seem to be due to a reduced coronal activity. In fact, Algols share many similarities with the radio behavior of RS CVns and the 5 GHz luminosity functions of both kind of systems look quite similar.

Among the different possibilities, the high radio variability and distances, which, on average, are larger than those of RS CVns, seem to be the most reasonable explanation for the apparently reduced activity at radio wavelengths.

Key words: stars: binaries: eclipsing – stars: activity – radio continuum: stars

1. Introduction

Algol type binaries are semi-detached systems where the secondary, usually a G-K subgiant or giant, fills its Roche lobe, and the primary is a B-A main sequence star. Furthermore, the evolved secondary is transferring mass to the primary. Although Algol systems are different from RS CVn systems, mainly from an evolutionary point of view, they exhibit some of the RS CVn activity phenomena. The similarities of secondaries together with the fact that in both cases the secondary components are synchronous fast rotators, have led to the suggestion that the secondaries of Algol systems could be the seat of magnetic activity (Hall 1989).

The observations of emission at radio and X-ray wavelengths and of flare-like events in Algol systems have confirmed the presence of magnetic activity and, quite recently, Richards & Albright (1993) have pointed out much evidence for magnetic activity in a sample of short-period Algol-type binaries. The key question is to what extent the activity of secondaries in Algol systems is similar to that of RS CVns.

It should be stressed that while in RS CVn binaries the magnetic activity can be studied at optical, UV, radio and X-ray wavelengths, in Algols, the spectrum of the active components is highly contaminated by the early primary and thus is not possible to use the conventional chromospheric-coronal diagnostics such as CaII H & K, Mg II h & k and other UV emission lines. However, stars with spectral type between B3 and A7 possess neither strong winds nor subphotospheric convention zones and thus cannot significantly contribute to the X-ray or radio emission. This makes radio observations one of the best way to study the non-thermal activity of the cool component of these systems. Despite the fact that Algol itself was one of the first stars detected at radio wavelengths (Wade & Hjellming, 1972), the knowledge of radio properties of Algol-type binaries is still very poor.

Slee et al. (1987) carried out a radio survey of southern active stars, including a number of Algol-type stars, by using Parkes radio telescope. They detected 14 out of the 47 observed systems with a typical standard error of $\sim$ 1.5 mJy, but, later on, they pointed out that only 8 of their detections could be classified as classical (EA2-type) Algols (Stewart et al., 1989).

Elias (1990) and Elias & Güdel (1993) observed a sample of Peculiar Emission Line Algols, as they classified a group of binaries which are supposed to be in the evolutionary phase between β Lyrae and Algol. Those systems, strictly related to classical Algols, are strongly interacting binaries and show radio fluxes whose characteristics, as spectral index and lack of variability, seem to indicate a thermal origin for the radio emission (Güdel & Elias, 1996).

We believe that very probably the observed radio flux originates from an expanding nebula, which embraces the entire system, rather than being related to the magnetic activity of the cool component and we will exclude these surveys from the following analysis.

Send offprint requests to: G. Umana, (umana@ira.noto.cnr.it)

A systematic study of radio emission from Algols was undertaken by the present authors with the aim of investigating whether the Algols resemble the RSCVns to any degree or if they constitute an entirely separate class of radio emitting stellar system. In the first partial survey, carried out at 6 cm, using the VLA (Umana et al., 1991), we detected 7 out of 14 observed systems. On the base of the inferred brightness temperature we excluded the thermal origin of the radio emission and showed that characteristic radio luminosity is very similar to that observed in the RS CVns.

Subsequently, four-frequencies radio spectra of the brightest systems of the original sample were obtained. They were well fitted by a model of non-homogeneous gyrosynchrotron emitting plasma (Umana et al., 1993) with a core-halo coronal structure.

Algol-type systems generally undergo a moderate mass transfer between the components, which is revealed by optical photometric and spectroscopic observations. In many cases there is also evidence of a permanent or transient disk around the hot component (Albright & Richards, 1995; Richards et al., 1995). On the contrary, this peculiarity has never been observed in RS CVns. A more detailed investigation of Algols' behaviour in the radio domain could also clarify if the presence of mass-transfer and of a disk plays any role in the radio emission.

The number of known Algol-type systems which exhibit radio emission is rather too low to draw a reasonable generalization of the observed phenomena. We present here the second part of our survey aimed at extending the Algol radio sources to a statistically significant sample for a better comparison with the RS CVn-type.

2. Observations and results

A large sample of well known Algol systems, whose observed properties are well documented in the literature (Giuricin et al., 1983), was examined to select the targets of our survey . From this original sample, we extracted the systems satisfying the following selection criteria:

- the secondary is late-type star with significantly deep convective envelopes, and is in contact, or nearly in contact with its Roche lobe.
- the binary period is less than 20 days. This criterion, the same adopted for RS CVns, ensures a fast rotation rate because the components, being tidally locked, are synchronous rotators.
- The distance is less than 400 parsecs. Sources of 30-50 Lu (1 Lu is 10^{15} erg cm^{-2}s^{-1}Hz^{-1}) should be detectable at the VLA sensitivity limit of few tenths of mJy.

Subsequently, it was suggested by a referee that we use the Brancewiz & Dworak (1980) compilation for distances, since these may be more accurate than the values that were originally used. The distance selection criterion is, therefore, not valid for some sources in the sample when we adopt the Brancewiz & Dworak distances.

The optical properties of the resultant sample are reported in Table 1, where spectral classifications, orbital/ rotational periods, radii and masses for both components are listed together with distances.

The observations were carried out by using the VLA [1] at 4.9 GHz with a total bandwidth of 100 MHz, in four different runs from October 1992 to April 1993. The choice of the observing frequency was a compromise between sensitivity and the large number of radio observations of Algol and RS CVn systems available at that frequency for a comparative study. We also obtained a VLA five frequencies radio spectrum, up to 22 GHz, of the well known Algol-type system RZ Cas.

For each source a nearby phase calibrator was used and the flux scale was fixed by daily observations of 3C286 and/or 3C48. The data were edited, calibrated and mapped using the **A**stronomical **I**mage **P**rocessing **S**ystem (AIPS) i.e. the standard programs of the NRAO . To achieve the highest possible signal to noise ratio, the mapping process was performed by using the natural weighting and, in case of sufficient S/N the dirty map was **CLEAN**ed down as close as possible to the theoretical noise. The source position and the flux density determination were obtained by the fit of a gaussian brightness distribution (JMFIT). We estimated the noise level in the maps by analyzing a map area reasonably far away from the phase center, consistency with the expected theoretical noise was also checked.

The results of this survey are summarized in table II as follows: columns 1 and 2, source identification, columns 3, 4 and 5, the measured radio flux density or its upper limit (3σ), the noise level in the map, and the radio luminosity, calculated by using distances as reported in Table 1; in columns 6 and 7, the observing date and the array configuration. Altogether we detected 6 out of the 26 observed systems.

3. Activity level in Algols

The 1992-1993 VLA survey leads to a radio detection rate of $\sim$ 30%, including our previous survey (Umana et al., 1991) and the work done by Slee et al. (1989). This results, compared to the detection rate (57%) obtained for RS CVns (Drake et. al., 1989; 1992), seems to indicate a reduced magnetic activity for Algol systems, at least at coronal level. However, The RS CVns sample consists of multiply observed systems and if only single observations (Drake et al., 1989, table 2) are considered a detection rate of 42 % is derived, which is closer to the 30 % value obtained for Algols.

White & Marshall (1983) noted a tendency towards smaller X-ray luminosities compared to RS CVns. This result has been recently confirmed by Singh et al. (1996), who compared the X-ray properties of Algols and RS CVns, by using a larger sample, consisting of systems observed with ROSAT satellite. Both authors considered possible causes of the reduced X-ray activity of Algols respect to the RS CVns. Among others, the influence of Roche-Lobe overflow on enhanced X-ray emission, as claimed for RS CVns by Welty & Ramsey (1995), is ruled out

[1] The Very Large Array is a facility of the National Radio Astronomy Observatory which is operated by Associated Universities, Inc. under cooperative agreement with the National Science Foundation

Table 1. Optical properties of the sample

Star	*HD*	*Spectral Classification*	*Period*[a] *Days*	$(R_1/R_\odot)^a$	$(R_2/R_\odot)^a$	$(M_1/M_\odot)^a$	$(M_2/M_\odot)^a$	*Distance*[b] *pc*
TW And	BD +32 4756	A8+K2	4.1228	2.2	3.3	1.8	0.4	256
TV Cas	1486	A0+F7IV	1.8126	3.2	3.1	3.8	1.6	333
U Cep	5679	B7V+G8III-IV	2.493	2.8	4.9	4.2	2.8	208
X Tri	12211	A3+G3IV	0.9715	1.71	1.96	2.3	1.2	303
TW Cas	16907	B9V+K4-K5	1.8126	2.7	1.9	2.9	1.2	588
RW Tau	25487	B8V+K0IV	2.7688	2.9	3.9	5.4	1.0	400
RT Per		F2V+G9IV	0.8494	1.41	1.27	1.71	0.42	294
RS Lep	40640	A2+M0	1.2885	2.0	2.2	2.6	0.8	500
IM Aur	33853	B9+K3IV	1.2473	3.11	2.26	4.4	1.1	435
AL Gem	266913	F5+K7	1.3913	1.5	1.1	1.3	0.1	227
S Cnc	74307	B9V+G8IV	9.4846	2.1	5.0	2.4	0.1	476
RX Hya	78014	A0+K2IV	2.2816	1.7	2.4	1.68	0.40	250
RS Vul	180939	B5+G2IV	4.4777	5.5	4.2	4.4	1.4	345
TZ Eri		F8+K0	2.6061	1.51	1.92	1.45	0.98	167
U CrB	136175	B6+F2IV	3.4522	3.0	4.6	4.8	1.4	500
V338 Her		A9+K5	1.3057	1.9	1.5	1.8	0.3	435
TZ CrA	167777	A0+K3IV	0.6867	1.6	1.1	1.8	0.5	556
KO Aql	173847	A0V+F8IV	2.8640	2.8	2.7	3.2	0.6	345
U Sge	181182	B7+G2IV-III	3.3806	4.2	5.5	5.7	1.9	227
V 346 Aql	191515	A0+G4IV	1.1064	2.2	2.0	3.2	1.0	435
ZZ Cyg		F7V+K5IV	0.6286	1.2	1.2	1.2	0.6	200
S Equ	199454	B8V+F0IV-V	3.4361	2.8	3.1	3.1	0.4	556
AW Peg	207956	A5V+F5IV	10.623	4.5	4.3	2.0	0.32	435
AT Peg	210892	A7V+K0	1.1461	1.9	1.7	1.7	0.8	370
DI Peg		F4IV+K3	0.7118	1.4	1.1	1.4	0.4	200
S Vel		A5V+K5III	5.9336	1.6	4.3	2.0	0.3	137

[a] From Giuricin et al., 1983
[b] From Brancewiz & Dworak, 1980

by this result, since Algols should be more luminous in X-ray than RS CVns. The most probable explanation of this difference could be related to the presence, in RS CVns, of large interacting intersystem loops, which produce an increased flare rate or can just contain larger quantities of X-ray emitting plasma.

Beasley et al. (1993) carried out a mini-survey of W UMa contact binaries with the compact array (CA) at 6 cm. More recently, Rucinski (1995) performed a high-sensitivity survey of a sample of 12 W UMa systems, by using the VLA at 3.6 cm.

W Uma systems consist of two late-type (F to K) main sequence stars, which are in contact and forced to very high rotational rate ($\sim 80 - 160$ kms^{-1}) by strong tidal coupling. W UMa stars are among the most active systems, at least at photospheric (Bradstreet & Guinan, 1988) and chromospheric (Vilhu and Heise, 1986) levels. However, Beasley et al. (1993) failed to detect, at radio wavelengths, any of the surveyed systems, while only 3, out of the 12 W UMas, were detected in the Rucinski's survey. Moreover, Rucinski (1995), by using also data from the literature, analyzed the temporal behavior of the radio emission of one of the detected systems, VW Cep, and pointed out that the system spent most of the time in radio quiescence. Radio flares are thus quite rare events, occurring for less than 20% of the time.

This seems to confirm what already noted by other authors: the coronae of contact binaries appear to be less active when compared to those of other kinds of magnetically active stars. The soft X-ray luminosities are over one order of magnitude smaller than those measured in RS CVns with similar activity levels as deduced from optical and UV observations. Moreover, the detection rate in the radio domain is particularly low, being only the 10%, at present. In this context, we may consider Algols as an intermediate case between RS CVns and W UMa, and consider the lower X-ray luminosities and radio detection rate as evidence for a less active corona. We may consider RS CVns-Algols-W UMas as sequence where coronal activity decreases as the convective components approach the contact with the inner Lagrangian surface.

Steady mass transfer between components can make the magnetic structures of the active components quite unstable and eventually the X-ray emission highly variable. This possibility was partially ruled out by recent ROSAT observations of β Per, which have revealed an X-ray light curve, stable over few orbital cycles (Ottman, 1994) and, possibly, over a longer time scale (Antunes et al., 1994). The variability of X-ray emission with orbital phase in W UMa binaries (Cruddace and Dupree 1985, Vilhu and Heise 1986) and in Algol (Stern et al. 1992, Antunes et al. 1994) as well as the partial X-ray secondary eclipse

Table 2. Radio properties of the sample

Star	*HD*	*Radio Flux Density* mJy	σ mJy	*Log Radio Luminosity* erg cm^{-2}s^{-1}Hz^{-1}	Date	
TW And	BD +32 4756	$\leq$ 0.15	0.05	$\leq$ 16.07	10/04/92	AD
TV Cas	1486	1.00	0.03	17.12	10/04/92	AD
U Cep	5679	2.80	0.03	17.16	10/04/92	AD
X Tri	12211	$\leq$ 0.12	0.04	$\leq$ 16.12	10/04/92	AD
TW Cas	16907	$\leq$ 0.12	0.04	$\leq$ 16.69	10/04/92	AD
RW Tau	25487	$\leq$ 0.12	0.04	$\leq$ 16.36	10/04/92	AD
RT Per		$\leq$ 0.15	0.05	$\leq$ 16.19	04/06/93	B
RS Lep	40640	$\leq$ 0.15	0.05	$\leq$ 16.64	04/06/93	B
IM Aur	33853	$\leq$ 0.15	0.05	$\leq$ 16.52	04/06/93	B
AL Gem	266913	$\leq$ 0.12	0.04	$\leq$ 15.87	04/06/93	B
S CnC	74307	$\leq$ 0.15	0.05	$\leq$ 16.60	04/06/93	B
RX Hya	78014	0.44	0.04	16.15	04/06/93	B
RS Vul	180939	0.26	0.03	16.57	04/25/93	B
TZ Eri		$\leq$ 0.21	0.07	$\leq$ 15.84	04/06/93	B
U CrB	136175	0.30	0.05	16.96	10/08/92	AD
V338 Her		$\leq$ 0.21	0.07	$\leq$ 16.67	04/06/93	AD
TZ CrA	167777	$\leq$ 0.24	0.08	$\leq$ 17.02	10/08/92	AD
KO Aql	173847	$\leq$ 0.12	0.04	$\leq$ 16.23	10/08/92	AD
U Sge	181182	1.0	0.05	16.80	10/08/92	AD
V 346 Aql	191515	$\leq$ 0.12	0.04	$\leq$ 16.43	10/04/92	AD
ZZ Cyg		$\leq$ 0.12	0.04	$\leq$ 15.76	04/25/93	B
S Equ	199454	$\leq$ 0.12	0.04	$\leq$ 16.65	10/04/92	AD
AW Peg	207956	$\leq$ 0.12	0.04	$\leq$ 16.43	10/04/92	AD
AT Peg	210892	$\leq$ 0.12	0.04	$\leq$ 16.29	10/08/92	AD
DI Peg		$\leq$ 0.12	0.04	$\leq$ 15.76	10/08/92	AD
S Vel		$\leq$ 0.15	0.05	$\leq$ 15.52	04/06/93	B

(Ottmann 1994) implies that emission is confined to low scale height structures. The reduced coronal activity may be the result of a smaller extension of closed loops allowed by the gravitational potential in the contact configuration.

To test this we will therefore compare the radio luminosity distributions for Algols and RS CVns. If it is the case of reduced coronal magnetic activity due to a reduced size of loop structures, we should see a significant difference between the two kinds of systems. Fig. 1 shows the 6 cm luminosity function of the Algol-type binary systems (shadowed region), superimposed to that of RS CVns. The latter has been obtained by using the compilations of Drake et al. (1989, 1992), who reported all the published 6 cm VLA data. The Algols data consist of the results of this paper, Umana et al. (1991) plus the mean radio luminosity of Algol, derived from data in the literature. For homogeneity we consider only 6 cm VLA detections thus not including the 6 detections of classical Algols reported by Slee et al., (1988). The distribution of Algol-type systems as a function of radio luminosity fairly matches that of RS CVns.

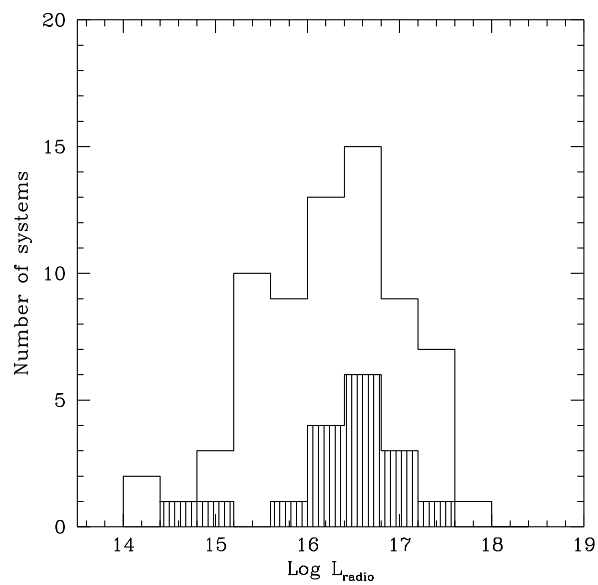

Fig. 1. Distribution of radio luminosity of the Algol-type systems (shadowed region) superimposed on that of RS CVns.

To better quantify the agreement between the two distribution functions, we follow the same approach as Singh et al. (1996), carrying out a statistical analysis on our data. In order to extract as much informations as possible from our database, we use the survival analysis, which is a technique that allows to include in the statistics also the upper limits (Feigelson & Nelson, 1985). A series of programs which perform survival analysis is contained in ASURV (Isobe et al. 1986) in the IRAF/STSDAS software package.

In Fig. 2 is reported, as cumulative radio luminosity function, the Kaplan-Meier estimator of the underlying distribution

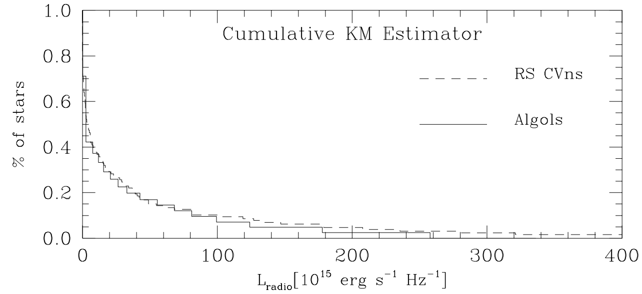

Fig. 2. The Kaplan-Meier estimator for Algol-type systems (continuos line) superimposed on that of RS CVns (dotted line).

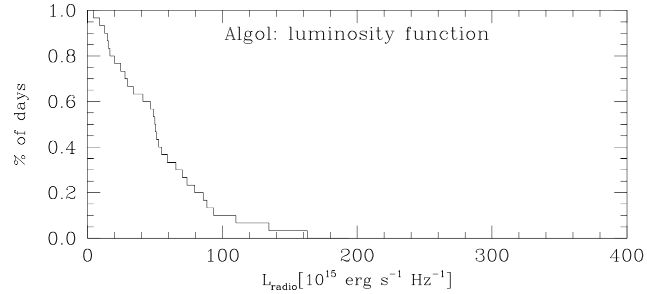

Fig. 3. Radio luminosity function of Algol at 6 cm. The data are extracted from Hjellming et al., (1972b; 1972b) and are obtained as an interpolation between 2.0 and 8.4 GHz observations.

Table 3. Results of two-sample tests

Gehan's Generalized Wilcoxon test (Permutation Variance)	85 %
Gehan's Generalized Wilcoxon test (Hypergeometric Variance)	85 %
Logrank Test	87 %
Peto & Peto Generalized Wilcoxon test	83 %
Peto & Prentice Generalized Wilcoxon test	82 %

function for both RS CVns and Algols. This time, from the original database, as described at the beginning of this section, we extract also all the upper limits (3 σ). The two distributions are very similar.

To further test this result, we use a series of procedures, such as Gehan's test, Logrank test and Peto and Peto test, which allow to establish whether two censored subsamples are drawn from the same parent population. The results of such an analysis are summarized in Table 3. The high value (from 87% for Logrank test to 82% for Peto & Prentice test) of probability that the two subsample are representative of the same population confirms what was already derived from Kaplan-Meier estimator.

The mean radio luminosity of the two subsample is $44(+/-11) \times 10^{16}$ erg cm^{-2}s^{-1}Hz^{-1} for Algols and $63(+/-15) \times 10^{16}$ erg cm^{-2}s^{-1}Hz^{-1} for RS CVns. This indicates that Algols show the same level of radio emission as RS CVns and confirms what was previously derived from a smaller sample of Algols and RS CVns (Umana et al., 1991).

The lower detection rate could than be attributed to the fact that in general, Algol-type systems are at higher distances than RS CVns and therefore detectable only during flaring episodes. The only system which has been sufficiently observed to determine a characteristic radio behaviour is Algol. Using the data of the remarkable systematic study of radio emission from this binary, carried out by Hjellming et al. (1972a; 1972b) with the NRAO three-element interferometer at 2.7 and 8.1 GHz, we derived the luminosity function distribution at 6 cm displayed in (Fig. 3). The flux density at 6 cm is being interpolated between 2.0 and 8.4 GHz values. From Fig. 3, we can estimate a probability of $\sim$ 50% to observe a radio flare in Algol with 6 cm luminosity higher than 50 Lu (1 Lu is 10^{15} erg cm^{-2}s^{-1}Hz^{-1}).

Adopting this luminosity function as representative of Algols as a class of radio sources and assuming that the radio emission has the same nature and characteristics as in Algol, the different observed flux level being exclusively due to a dilution factor, we find that the 50 % level corresponds to a moderate radio flare ($S_{6\ \rm cm} \geq$ 58mJy) for Algol (distance 27pc). But it becomes comparable to what we consider as quiescent level ($S_{6\ \rm cm} \leq$ 5mJy) for distances greater than 100 pc and it approaches the sensitivity threshold of VLA ($S_{6\ \rm cm} \leq$ 0.5mJy) for distances greater than 300 pc.

Algol systems in our sample are on average more distant than RS CVns. This would imply that if radio emission has the same origin in both types of close binaries we are detecting only the Algols at a moderate flaring activity level. If this level really has 50 % probability of being reached, the detection rate, down to the very quiescent level, could be near 60 %, as for the RS CVn systems. At the present we can therefore assume that, from Algols more distant than 300 pc, we are detecting only radio flares, but only with repeated observations we should be able to discriminate between flaring and quiescent emission; then we can confidently compare the detection rate with that of RS CVns.

4. Relations between radio emission and observations in other spectral regions

4.1. Radio and optical

Classical Algols are well beyond the most important phase of mass transfer but some mass flow is still present, with observational effects differing from one system to another. A permanent accretion disk will form in those systems where the size of the primary is smaller compared to the Roche lobe, while in the case of short period systems ($P_{orb} \leq 5-6$ days), the gas stream from the L1 point will directly impact on the surface of the primary.

Effects of mass exchange, in the form of gas streams and/or accretion disk, are evident in the light curves of Algols, which often exihibit out-eclipses distortions and variations of shape and duration of the primary minimum, and in the optical spectrum, where H_α is often observed in emission. Richards et al. (1995) applying the technique of Doppler tomography to the H_α

emission line profile, have imaged the gaseous stream pattern of a small sample of short-period Algols, namely U CrB, β Per, U Sge and RS Vul. All the observed systems, which are also radio emitters, exhibit different sources of H_α emission. Besides the gas streams and disk-like features, as expected from Roche lobe overflow, there is evidence of a third source of emission. The latter source appears to be associated with the secondary and, probably, is related to the magnetic activity of this component. The presence of a transient disk-like structure, as well as of highly variable H_α emission, have been reported for RW Tau (Vesper & Honeycutt, 1993), S Vel (Sahade 1952, Bond 1972) and RT Per (Sanwal and Coubey 1981). These systems, that belong to our sample, were not detected in the present survey. Therefore at the moment, the measured radio emission does not seem to have any clear relation with the presence of circumstellar material, as inferred from photometric and spectroscopic observations.

From accurate photometric studies Olson (1982) defined the systems U Cep, RW Tau, U CrB, U Sge and RZ Cas as "active Algols". These systems show evidence of optical light curve distortions and variations of the orbital period that cannot be easily explained in the framework of the classical model of transient disk (Olson, 1981; Narusawa et al, 1994). There have been suggestions that these variations are due to stellar spots and, indeed, from the analysis of the near-IR light curve of Algol, Richards (1990) concluded that the observed variations could be attributed to spots on the photosphere of the secondary. We have detected all of these as radio sources except for RW Tau. However, other systems showing some evidence of photospheric, and/or chromospheric activity, like S Vel and X Tri, are at distances closer than RW Tau and were not detected.

This suggests that there may be a minimum photospheric/chromospheric activity level above which systems would be detectable radio emitters, but more quantitative estimates of chromospheric activity are needed before this can be to definitively demonstrated.

Olson & Etzel (1993), who monitored the magnitude of the secondaries of 6 short-period Algol-type binaries in a long-time scale, found a correlation between the amplitude of the magnitude variations and the rotational velocity for 5 systems of the sample, including S Cnc and X Tri but U Sge. The number of studied systems is still quite low and it is hazardous to draw definite conclusions, but it is worth to note that U Sge is the only system in the sample that is a radio emitter and does not show this correlation. This type of relation is not observed in RS CVns and, this is usually attributed to a saturation effect and to a uniformly distribution of spots on the stellar surface. The more uniform is the distribution the smaller is the amplitude of the light variation.

In conclusion, it seems that those Algols, which are also radio sources, share, in the optical, some similarities with the RS CVn-type binaries, showing the same kind of magnetic activity indicators, such as stellar spots, Hα and Ca II emission.

4.2. Radio and X-ray

Soft X-ray and microwave emissions are usually assumed to be indicators of coronal activity. Both types of coronal emission have been observed in RS CVn systems and possible relations between them has been discussed by different authors.

Drake et al. (1989, 1992) found a power law between the soft X-ray luminosity and the 6 cm radio luminosity, ($L_{6\ \rm cm} \sim L_X^{1.30\pm0.13}$), by considering a large data base of non-simultaneous observations. Recently Fox et al. (1994), using simultaneous ROSAT/VLA observations of 10 RS CVn-type systems, confirmed this proportionality. On the basis of the correlation, these authors suggest that the same electron population contributes to X-ray and to radio non-flaring fluxes, thus providing a reasonable explanation for the origin of the quiescent radio emission from RS CVn-type. In the first paper Drake et al. (1989) proposed that during quiescent states both X-ray and radio emission in RS CVn systems are due the high temperature (T$_e \approx 5 \times 10^7$ K) thermal electron population, later they (Drake et al. 1992) rediscuss the problem concluding that gyrosynchrotron from nonthermal electrons is the most natural explanation for the radio emission, remaining still open the explanation of the common origin for the radio and X-ray emission. Finally, Güdel & Benz (1993) and Benz & Güdel (1994) showed that a linear relationship between $log(L_{6\ \rm cm})$ and $log(L_X)$ exists not just for RS CVns but also for different types of stellar objects, including solar flares, and holds up to 5 order of magnitude. These authors concluded that the explanation for such a correlation must be found in the primary process of energy release, which takes place in the corona of active stars. More specifically, a connection must exists between the energy which goes to heat the local thermal plasma and the energy necessary to accelerated the non-thermic radio emitting particles.

From the most recent study on X-ray emission from Algols (Singh et al., 1996) it turns out that Algols have reduced X-ray luminosities when compared to RS CVn-type. On the contrary, from the present work no significative difference in the radio behaviour is evident.

At this point it could be extremely interesting to establish whether a linear relationship holds also between $logL_{radio}$ and $LogL_X$ in Algol-type. The sample of systems for which both X-ray and radio measurements are available is quite small, consisting of the X-ray data of Singh et al. (1996) and radio data of Umana et al. (1991) and the present work. We can add four more targets when considering also the systems observed previously with the Einstein Observatory (White & Marshall 1983; McCluskey and Kondo, 1984). Because these latter measurements were obtained with a quite different instrument, in the following analysis they will be treated separately. Since we are dealing with a data base that includes a certain number of upper limits we use the programs available in the IRAF/STSDAS software package, which allow to handle properly censored data.

We first calculate the generalized Kendall's τ and the Spearman's rank order ρ correlation tests to check if the radio and X-ray luminosities of the sample stars are correlated. The results of such tests are reported on Table 4. There is a probability of

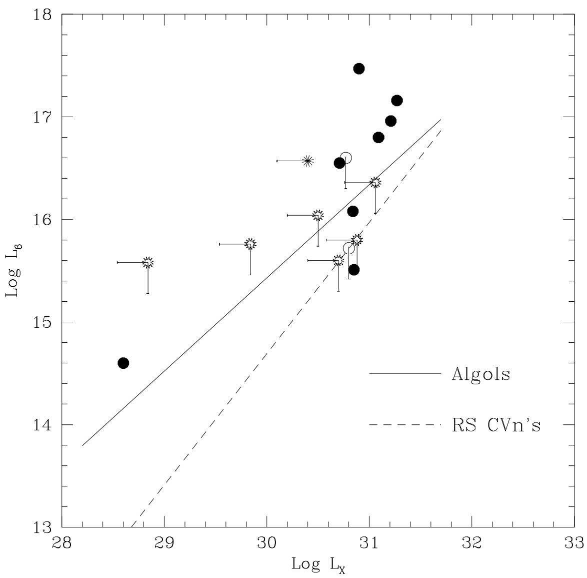

Fig. 4. The linear relationship between X-ray and radio luminosities of Algols. The full line represent the linear regression as derived by applying the Bucley-James methods. The full dots are the detections while the other empty symbols represent censored data. As comparison, the relationship derived for RS CVns is also showed (dashed line)

Table 4. Results of correlation tests

	Rosat sample	complete sample
generalized Kendall's τ	97 %	99 %
Spearman's rank order ρ	85 %	98 %
Slope	0.91 ± 0.32	0.91 ± 0.26

97% that the two quantities are correlated. This probability goes up to $\sim$ 99% when the other four sources from Einstein sample are also included.

The linear regression analysis between $logL_{radio}$ and $LogL_X$ is carried out by using the Buckey-James methods. The derived slope, together its standard deviation, is reported on Table 4, while in Fig. 4 the data points, including the Einstein data set, are showed (full line) together the regression line. The empty stars data points represent the data with censoring in both variables which were not considered in the linear regression analysis. For comparison, the regression line for the relation holding for RS CVns is showed as a dashed line (Drake et al. 1992).

Despite the results of the correlation test, an inspection of Fig. 4 reveals that the $logL_{radio}$ and $LogL_X$ correlation is strongly biased by the data point that corresponds to αCrB, i.e. $logL_{radio}$ = 14.6 (Umana et al., 1991) and $LogL_X$ = 28.6 (Singh et al., 1996). This system, however, can not be considered an Algol in the classical sense, since the filling factor of its secondary Roche-Lobe is 7% (Singh et al., 1996), very far from the 100% value that a classical Algol should have. Excluding the αCrB data point from our analysis, the possible correlation results much weakened. In particular, while the radio luminosity values scatter between 2 dex, the values of X-ray luminosities are all around L_X = 31.0 At this state, we can say very little about a possible correlation between X and Radio luminosities in Algols and more data points are needed to firmly establish if a linear correlation between $logL_{radio}$ and $LogL_X$, similar to what is observed for RS Cvns, holds also for Algols. We may conclude that while the radio behaviour of these two classes of objects appears to be indistinguishable, as has been demonstrated by the present work, implying that a common radio emission mechanism is likely, the X-ray to radio behaviour shows a very large scatter.

It is, however, worthwhile to point out that in the $logL_{radio}-LogL_X$ diagram (i.e. Fig. 4) most of the Algols lie well above the RS CVns regression line, reinforcing the conclusions, reached by Singh et al. (1996), that Algols are 2-3 times less luminous in X-ray than RS CVns.

The results of the present analysis seems to exclude a common origin for the radio and X-ray emissions in Algols, since if this was the case, we should observe a clear proportionality between radio and X-ray luminosities. This raises the question on the origin of the quiescent radio emission that in RS CVNs has been proposed to be in related to the X-ray emission (Drake et al., 1989; Drake et al. 1992; Güdel & Benz, 1993).

The possibility that the observed radio emission in Algols could be produced by thermal bremsstrahlung or associated to mass flow was already ruled out by Umana et al. (1991). Also the alternative possibility of thermal gyrosynchrotron has been excluded by radio spectra obtained at four frequencies for a limited sample of Algols (Umana et al. 1993). The slope of the optically thin region of the observed radio spectrum is strictly related to the energy spectrum of the radiating particles. If the radio emission is due to the same thermal electron population, which produces the X-ray flux, an homogeneous source would have a characteristic radio spectrum with a well defined flux density decrement ($S_\nu \propto \nu^{-8}$) (Dulk & Marsh, 1982). Our spectra were rather flat at low frequencies and exhibit a turnover between 5 and 10 GHz. We found that these observations could be fitted quite well by gyrosynchrotron emission of an inhomogeneous source of non-thermal electrons. A core-halo structure was assumed. The characteristic size of the core was found to be comparable to the size of the active component, while the halo should be comparable to the size of the entire system.

To furtherly test this hypothesis, we observed the Algol system RZ Cas, with the VLA at 5 frequencies, up to 22 GHz. The observations were carried out and reduced following the standard procedures (see Sect. 3.2).

The observed five points spectrum is showed in Fig. 5, where the optically thick-thin transition is well evident between 1.5 and 5 GHz. The optically thin part is quite flat with a spectral index $\alpha \sim$ 0.30, i.e. very similar to the system spectra in the previous sample.

We thus conclude that the observations exclude the possibility of a thermal origin of the low level radio emission of Algol-type systems. However, there is evidence that also the quiescent radio emission from Algol is highly variable, and at

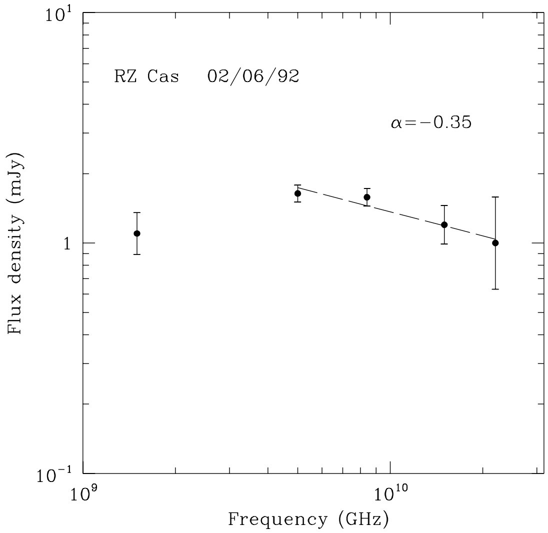

Fig. 5. The five points radio spectrum of RZ Cas. A linear fit of the optically thin part is showed. The errorbar, associated to each data point, represents the rms of the map.

least structured in two main components. The variability seems to indicate that probably microflaring activity could be the main responsible for the low level average flux (Lefevre et al., 1994).

5. Conclusion

By combining the results of the present survey with previously published data we were able to derive the main characteristics of Algols' radio emission.

There are no significant differences between radio emission of Algols and RS Cvns, as can be inferred from the comparison between the two luminosity distribution functions. This is in contrast with what has been derived from X-ray studies, which showed that Algol-type systems are less luminous than RS CVns.

The systems detected at radio wavelengths show, in other spectral regions, the same features of the magnetic activity observed in RS CVns. This suggests that, not only the two kinds of systems show the same level of radio emission but also that the radio flux is strongly related to the magnetic activity of the late type component, because the primary, an early-type stars without external convective layers, is not expected to be magnetically active. This would imply that, to produce a sizable radio emission, a sufficient condition is the presence of a K IV-III component, and it is not necessary to invoke models involving giant intersystem magnetic structures originating from the interaction of magnetic fields of both components.

The reduced detection rate, compared to that of RS CVns, can be attributed to the fact that Algols are, on average, more distant than RS CVns. This makes radio detections more rare, as only luminosities reached during flares correspond to detectable radio fluxes. This explains why RW Tau, which is at 360 pc and share many characteristics, such as photometric and H_α variability with other nearby detected systems, has not been detected.

The presence of mass-transfer between components does not seem to play an important role as enhancement factor for radio emission. As a matter of fact, rather distant systems with evident signatures of circumstellar material were not detected in the present survey. The same conclusion has been reached in the case of X-ray emission, as one would expect, on the contrary of what observed, that the Roche-lobe filling Algol-type systems be more luminous than RS CVns.

Some mass flow could, perhaps, trigger radio flares while interacting with magnetic structures of the active component. Future radio observations coordinated with Hα spectroscopy need to be focused in that direction.

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