NONTHERMAL MICROWAVE PHENOMENA IN OTHER STARS

R. M. Hjellming
National Radio Astronomy Observatory*, Socorro, NM,

D. M. Gibson
New Mexico Institute of Mining and Technology, Socorro, NM

ABSTRACT

Several classes of "normal" stellar objects exhibit microwave phenomena, predominantly at cm wavelengths. These include RS CVn binaries, Algol-type binaries, M supergiants, and UV Ceti-type flare stars. The emission mechanisms are generally either synchrotron or gryosynchrotron radiation, with the latter being predominant in the numerous RS CVn radio emitters which sometimes exhibit variable circular polarization. "Events" have time scales varying from minutes to days.

1. TYPES OF VARIABLE MICROWAVE EMITTING STARS

Other stars besides the sun which exhibit continuum radio emission can be broadly categorized as either free-free bremsstrahlung emitters or highly variable nonthermal emitters. Roughly 50 objects are now known to be in the former category, and although they are of little interest to us here, they represent various extremes of stellar wind or ejected circumstellar envelope phenomena. We exclude from our discussion the radio flaring X-ray stars (Sco X-1, Cyg X-1, Cyg X-3, Cyg X-2, GX17+2, etc.) which show a bizarre and poorly understood variety of nonthermal flaring, including synchrotron events which are quasar-like in behavior. The variable nonthermal radio stars exhibit considerable similarities to solar events. However, they are dominantly cm-wavelength objects, and the radio luminosities range from 10^{13} to 10^{18} ergs/sec Hz, so the larger flares have observable and inferred energies 10^5-10^6 times those for the largest solar events. The remaining radio stars that we will discuss are the UV Ceti flare stars, the active or flaring supergiants and what we will call the active binaries.

*The National Radio Astronomy Observatory is operated by Associated Universities, Incorporated, under contract with the National Science Foundation.

M.R. Kundu and T.E. Gergely (eds.), Radio Physics of the Sun, 209-220.

https://doi.org/10.1017/S007418090003686X Published online by Cambridge University Press

2. UV CETI-TYPE RADIO STARS

UV Ceti and YZ CMi are prime examples of a small (~7) group of stars that flare at optical wavelengths and show short time scale meter-wavelength events. Observations of this class of objects were pioneered by Lovell (1969) at Jodrell Bank. Recent work at Jodrell Bank (Davis et al. 1978) using long baseline interferometers, with techniques to discriminate amongst confusion, interference and stellar signals, has resulted in the first unambiguous observations of flare-star radio events. Previous observations were considered to be stellar in origin rather than interference on the basis of approximate simultaneity with optical flares. There is therefore a possibility that some previous cases were not real. Fortunately, we can now discuss unambiguous results obtained by methods such as used by Davis et al. 1978. For example, they observed a 408-MHz radio flare in YZ CMi which lasted three hours and contained 2.8×10^{25} ergs in a 4-MHz bandwidth. This is about 10^6 times the energy in a large solar flare of importance 3. The luminosity of 6×10^{14} erg/sec Hz is on the low side of the observed range for active supergiants and binaries. Davis et al. have also observed a flare in UV Ceti a factor of six weaker than the YZ CMi event. Unfortunately, the very rare events discussed by Lovell (1969), which are thousands of times stronger, have not yet been observed with the new interferometric techniques.

3. ACTIVE RADIO SUPERGIANTS

As listed in Table I, four red supergiants have been observed to flare sporadically. Unfortunately, in most cases only detections at levels not seen at other times have been made, and most of the time only one frequency and one antenna were involved.

TABLE I. ACTIVE SUPERGIANTS

Name	Sp. Type	Dist. (pc)	Flux (Jy)	Freq. (GHz)	Luminosity (10^{15} erg/sec Hz)	References
α Ori	M2 Iab	200	110	15	5300	1,2
α Sco A	M1Ib	180	2.3	5	89	3,4
R Aql	gM5e-8e	150	240	10.5	6500	5
π Aur	M3II	170	31	10.6	1100	6

References: 1, Kellermann and Pauliny-Toth 1966; 2, Altenhoff and Wendker 1973; 3, Hjellming and Wade 1971; 4, Gibson 1979; 5, Woodsworth and Hughes 1973; and 6, Seaquist 1967.

The only observation of a star listed in Table I that involved more than one frequency and multiple interferometer pairs was the Gibson (1979) observation of a 1978 July 21-22 event in α Sco A. This event reached a level of 2 mJy at 6 cm, with an upper limit of 1 mJy at 20 cm, so for a distance of 180 pc the 6-cm event had a luminosity of

9×10^{16} erg/sec Hz. Using the high resolution capabilities of the VLA Gibson (1979) was able to show that the above-mentioned event was coincident with α Sco A. At the same time the radio source near the B4V companion, α Sco B, which was previously known (Hjellming and Wade 1971), appeared between the two stars but close to α Sco B. From its location it seems likely that the α Sco B radio source is related to a bow shock similar to the earth's bow shock, except that in this case it is formed by the interaction of the Antares stellar wind and the B4V wind and/or magnetosphere.

The transient radio flares in the supergiants listed in Table I may be correlated with the extremely large, dark "star-spots" observed on some of these systems. Unfortunately the type of radio data presently available are not enough to give us the spectrum, polarization and time variation information that would give us clues as to the physical processes producing the radio events.

4. ACTIVE BINARIES

The class of variable, nonthermal radio stars which are most common and about which we have the most information are those we will call the "active" (normal) binaries. In Table I we list the currently known properties of 21 objects that unambiguously have variable radio emission associated with binary stars. We have not included a number of other possible or marginal detections. One of the most interesting aspects of this table is that the only systems that are not RS CVn and related binaries are β Per (Algol), β Lyr, b Per, CC Cas, and α Sco B. As mentioned above, there is some question about how to classify the radio source near α Sco B; however, because its existence is dependent upon the M1Iab star and the B4V star being close to each other, as in a binary system, we include it in this group. The other active binaries may or may not have interacting wind/magnetosphere phenomena. In the case of CC Cas, the variable radio source may be thermal bremsstrahlung from a stellar wind, since the Lyman continuum of the stars would be sufficient to maintain the ionization of the wind.

Because of the importance of the RS CVn binaries, let us briefly mention their main characteristics. "True" RS CVn's have (Hall 1976, Zeilik et al. 1979): periods between 1 and 14 days, strong emission in the H and K lines of CaII and a star of type F or G coupled with a cooler star of type late G or early K. Of the 16 stars we have described as RS CVn's in Table II, 5 have longer periods than allowed by the formal definition of the class and one has a slightly shorter period. Many RS CVn's have recently been found to be soft X-ray sources (Walter et al. 1978) with typical temperatures of 10^7 K. This is somewhat hotter than the solar X-ray corona, but is still considered to be direct evidence for coronae in these stars. Variable UV emission lines also give clear evidence of extensive chromospheric activity. Some RS CVn's are known for apparent dark areas (star-spots) covering up to 40% of one hemisphere of a stellar disk. For example, RS CVn and RT Lac appear to have "migration" periods of about 10 years for the

TABLE II. ACTIVE BINARIES

Name	Period (days)	Dist. (pc)	Spec. Types	Max. Flux (mJy)	Max. Luminosity (10^{15} erg/ sec Hz)	Freq. (MHz)	Ref.
λ And	20.5	23	G8III-IV+?	20	13	8085	1,3
UX Ari	6.4	55	G5V+K0IV	200	720	8085	2
54 Cam	11.1	38	G0V+G2V	12	21	5000	3
RS CVn	4.8	145	F4IV-V+K0IV	7	180	4885	4
σ CrB	1.1	23	F8V+G0V	57	36	14700	3
RZ Eri	39.3	105	F5V+G5IV	4	53	8085	5
σ Gem	19.6	59	K1III+?	19	79	4885	5,3
AR Lac	2.0	47	G2IV-V+K0IV	500	1300	10600	6,7
HK Lac	24.4	150	FIV+K0III	25	670	10600	8
RT Lac	5.1	205	G9IV+K1IV	35	1800	8085	9
SZ Psc	4.0	100	F8V+K1IV-V	100	1200	10500	10,3
UV Psc	0.9	125	G2IV-V+K3IV-V	14	260	5000	3
V711 Tau	2.8	33	G5V+K0IV	1200	1600	10600	11
HD 216489	24.6	200	gK1+?	33	1600	5000	3
HD 224085	6.7	29	K0IV-V+?	92	93	4885	3,10
HR 5110	2.6	52	F2IV-V+?	425	1400	10760	12
CC Cas	3.4	1000	O9IV+O9IV	10	12000	8085	7
β Lyr	12.9	260	B8p+?	20	1600	8085	13
b Per	1.5	56	A2IV+G+F5V	12	45	8085	14
β Per	2.9	25	B8V+G5III+A7m	1020	760	8085	13,15
α Sco B		180	B4V(+M1Iab)	10	390	8085	16

References: 1, Bath and Wallerstein 1975; 2, Gibson *et al*. 1975; 3, Spangler *et al*. 1977; 4, Gibson and Newell 1979; 5, Gibson and Owen 1979; 6, Hjellming and Blankenship 1973; 7, Gibson and Hjellming 1974; 8, Feldman 1979a; 9, Gibson *et al*. 1978; 10, Owen and Gibson 1978; 11, Owen *et al*. 1976; 12, Feldman 1979b; 13, Wade and Hjellming 1972; 14, Hjellming and Wade 1972; 15, Hjellming *et al*. 1972; 16, Hjellming and Wade 1971.

dark spot moving with respect to the binary period; this may indicate that synchronous rotation fails by just 0.14% in these systems.

The active binaries that flare the strongest at radio wavelengths are, of course, the best studied. Thus the ones that we have the most information about are β Per (Algol) and V711 Tau (HR1099). The next largest amount of information is available for AR Lac and UX Ari. Most of the other stars in Table II have been just detected, and in many cases significant events have been observed at only one frequency. We have already mentioned the unique information that we have about the α Sco B radio source. Its probable character as a bow shock or interacting wind/magnetosphere phenomena may indicate a type of phenomena occurring in some of these other systems. As representative of the other systems let us now discuss β Per and V711 Tau.

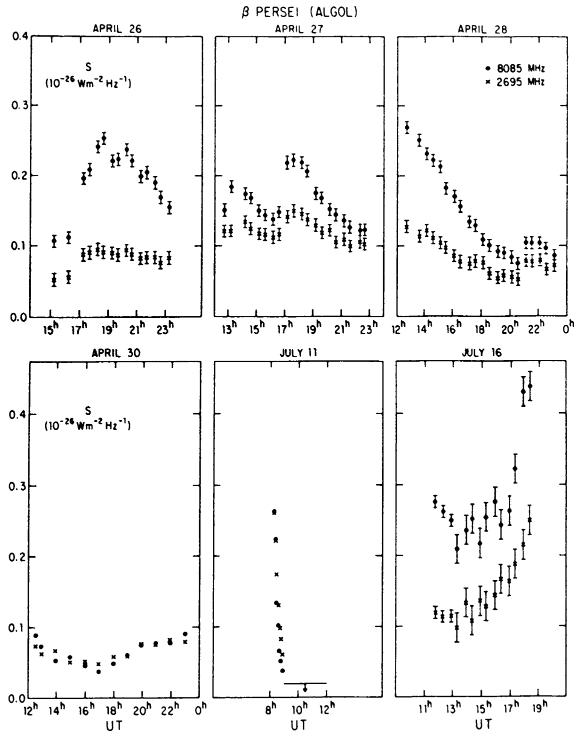

Fig. 1 - Six sample radio events observed in β Persei.

β Per has probably had, up to this time, the largest investment in total observing time, particularly from 1971 to 1975. Fig. 1 shows a set of six radio "events" which represent much of its typical behavior (Hjellming et al. 1972). The data for April 26-28 and July 16, 1971 represent fairly typical "events" or portions of events in β Per. The only phenomena in these four days that have not been too common are the "discontinuities" where typical variations are changed by a sudden increase in overall level that can take place in as little as five minutes. Cases like April 26 in Fig. 1, where both a rise and a decay have been observed, have been used by Gibson (1976) to derive a "mean" β Per event shape as shown in Fig. 2. The points plotted in Fig. 2 consist of separate observations normalized to an average mean flux density. The lines in Fig. 2 then show the average rise and decay curves. This shows that: (1) decay time for an event is typically twice the rise time; (2) the events always peak at the same time at 2696 and 8085 MHz; (3) most events do not deviate very strongly from the typical; and (4) the spectrum steepens as the event rises, typically peaks at a spectral index of about 1 and flattens out again as the event decays. The previous discussion applies to the most common type of behavior. However, a few percent of the time the radio source appears to simply vary up and down with an apparently flat spectrum, as seen for the April 30 data in Fig. 1. More rare are a few cases where events have evolved into a clearly nonthermal decay after appearing more like the typical peaking events in Fig. 2. An unusual example of this is the July 11 decay in Fig. 1 which is shown to be a complete, unusually brief event of a couple hours duration when the Pooley and Ryle (1973) data are added as shown in Fig. 3. This is the shortest complete "event" and the most rapid decay yet seen in any active radio binary. As discussed by Gibson (1976) a plot of the ranges of flaring of β Per give the impression of "cycles of activity", that is, there are periods of weeks and months when the radio source is barely there at low levels, and there are other equally long periods when flaring appears to be a near daily occurrence. One has this general impression from the observations of all the active radio binaries, however, the frequency of observations has generally not been frequent or systematic enough to establish statistical significance or characteristics of flaring and nonflaring cycles.

Some of the most important radio observations of stars have been the VLBI observations of β Per that measured the size of the evolving radio source. Clark et al. 1975 and Clark et al. 1976 observed events reaching 0.7 and 1.02 Jy, respectively, finding that the sizes of the radio source were 8.0×10^{11} cm and 1.5×10^{12} cm, respectively. Since the stellar disks are 4.5×10^{11} cm and the semi-major axis of the system is

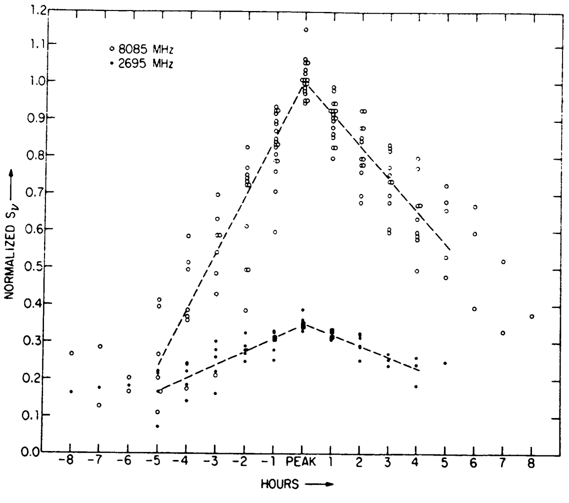

Fig. 2 - A composite peaking event in β Per formed by normalizing 22 separate events to the same 8085 MHz average flux density.

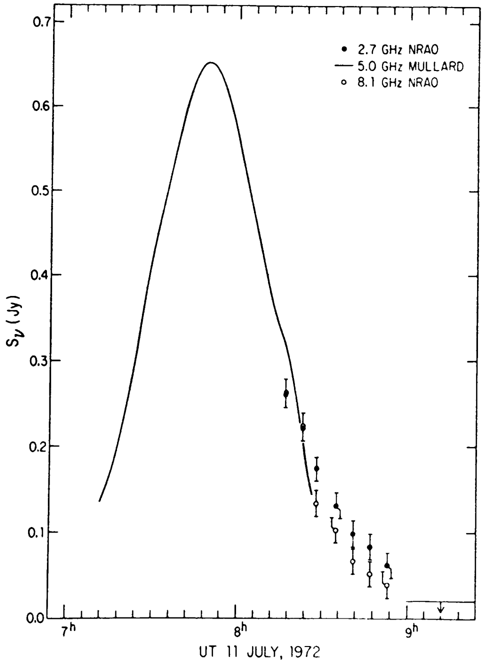

Fig. 3 - An usually brief event in β Per which ends in a nonthermal decay.

10^{12} cm, the radio sources are large compared to a stellar disk but close to the separation of the stars. The 0.7 Jy event of Clark et al. 1976, when interpreted as a synchrotron event, had energies of $5x10^{34}$ ergs and $4x10^{34}$ ergs in relativistic electrons and magnetic fields, respectively, at a time when the size scale was $1.5x10^{12}$ cm and the field was about 1 Gauss.

V711 Tau (HR1099) is a typical (best case) RS CVn radio binary. It has been studied very extensively because of its frequent flaring to high levels. As an example of day-to-day behavior Fig. 4 shows the flux density of V711 Tau from October 29, 1976 to November 15. In Fig. 4 the circles represent observations at 6 cm by Spangler et al. (1977) while the filled circles show 6-cm VLA observations by Hjellming and Brown (1979). The behavior from November 9 to November 15 shows a clear, single flaring event of several days duration, a time scale which occurs occasionally in RS CVn binaries but has never been seen in β Per. The decay observed on November 12-15 was observed at a number of other frequencies and showed an essentially constant nonthermal spectral index of -0.14. This occasional appearance of a decaying nonthermal spectrum is one of the strongest pieces of evidence for the presumption that the radiation process dominating these events is magnetobremsstrahlung. Like β Per and other radio binaries, V711 Tau

https://doi.org/10.1017/S007418090003686X Published online by Cambridge University Press

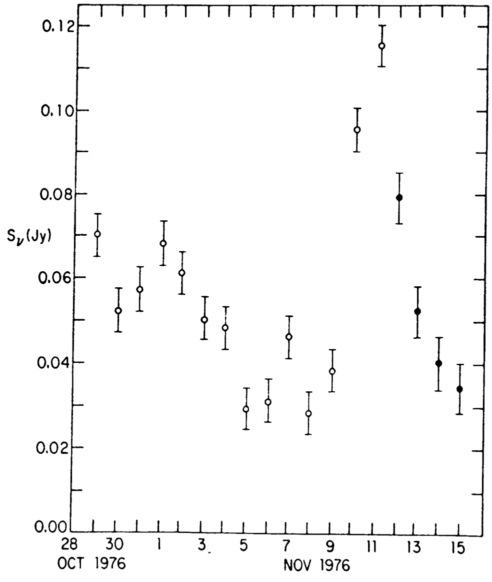

Fig. 4 - An example of long time scale time variations of V711 Tau (HR1099) at 6 cm.

has been observed in periods when strong flaring to high levels is a daily occurrence. Fig. 5 shows a segment of the 2.8-cm data of Feldman et al. 1978 when V711 Tau was flaring to the 1-Jy level. This was the time of an extensive campaign of radio, optical and X-ray observations of V711 Tau and other RS CVn stars which were described in a series of papers in a special December 1978 issue of the Astronomical Journal.

One of the most important features observed in RS CVn radio binaries is variable circular polarization. First discovered by Spangler (1977) in UX Ari, a stronger example of variable circular polarization was observed in V711 Tau by Owen et al. 1976. Fig. 6 shows an example of circularly polarized emission observed by Brown and Crane (1978) during the extensive V711 Tau flaring in February-March 1978. A major portion of this event showed up only in left circular polarization and only at 2695 MHz. Brown and Crane (1978) further showed that there were periods when the left circularly polarized flux was exhibiting an "oscillation" with about a four-minute cycle repeated every 5-6 minutes, as shown in Fig. 7. Understanding this behavior is clearly critical to our knowledge of these objects.

The frequent occurrence of circular polarization in objects like V711 Tau and UX Ari has been interpreted as strong evidence that the radio emission process is gryosynchrotron rather than occurring in the synchrotron regime. Other arguments indicate that the energies of the

https://doi.org/10.1017/S007418090003686X Published online by Cambridge University Press

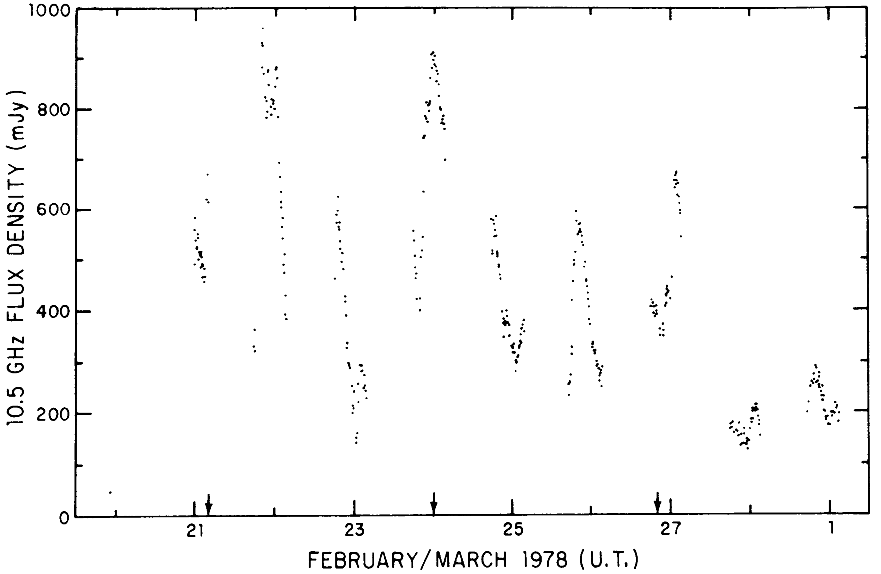

Fig. 5 - Behavior of V711 Tau (HR1099) at 2.8 cm during a period of unusually strong flaring activity.

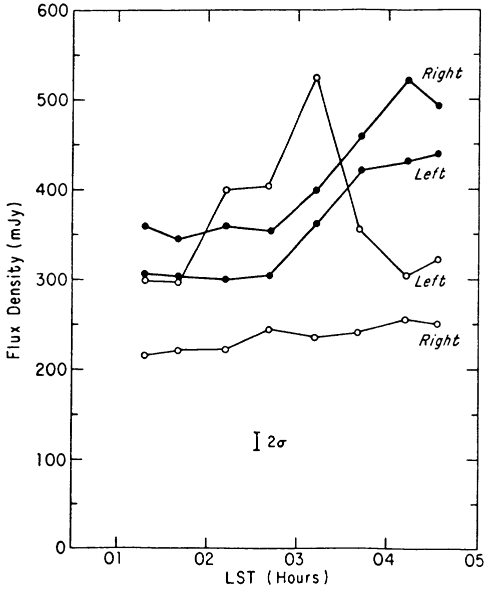

Fig. 6 - An event in V711 Tau (HR1099) showing circular polarization at both 2695 MHz (open circles) and 8085 MHz (filled circles), with a portion of the 2695-MHz event appearing only in left circular polarization.

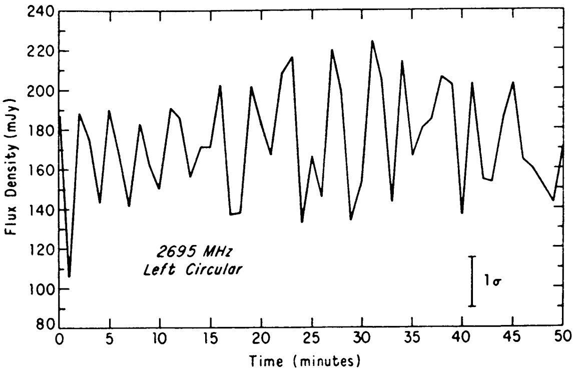

Fig. 7 - Four minute oscillations appearing in the 2695 MHz circularly polarized flux of V711 Tau (HR1099).

radiating particles are typically of a few MeV, which supports the conclusion that gyrosynchrotron radiation is important for the RS CVn binaries. Similar analyses indicate that β Per events are mostly in the synchrotron regime. Aside from the two frequency observations reported from the Green Bank interferometer, most radio star observations have not involved enough frequency and time coverage to clearly understand the spectral evolution of events. One of the few exceptions to this are the five frequency observations by Hjellming and Brown (1979) based upon simultaneous Green Bank interferometer and VLA observations. Fig. 8 shows a dynamic spectrum-type display of a pair of events observed December 2-3, 1977 for UX Ari. One of its important features is that the low frequency portion retains the typical slope of a self-absorbed radio source, and that the variable events therefore show up mainly at the highest frequencies. From the sparser two frequency data it is clear that this is a predominant feature in most radio star events which probably results from the unusually compact, high gas density regions where things happen in binary systems.

One of the most important questions to be faced is whether the binary star phenomena is critical for the occurrence of the radio emission in most stars. Gibson (1978) has conducted a survey of single stars similar in nature to RS CVn components, and these data together with the known detections and nondetections of radio stars make a clear case that stellar radio emission is more common in binary systems. There must be some property critical to the radio emission which is strongly enhanced by effects occurring in binary systems. One can speculate that this might be: (1) an enhancement of the dynamo mechanisms that generate magnetic fields; (2) a modified behavior of convective regions near the surface because of tidal effects; or (3) interacting wind/ magnetosphere effects such as known for the earth-sun system and pro-

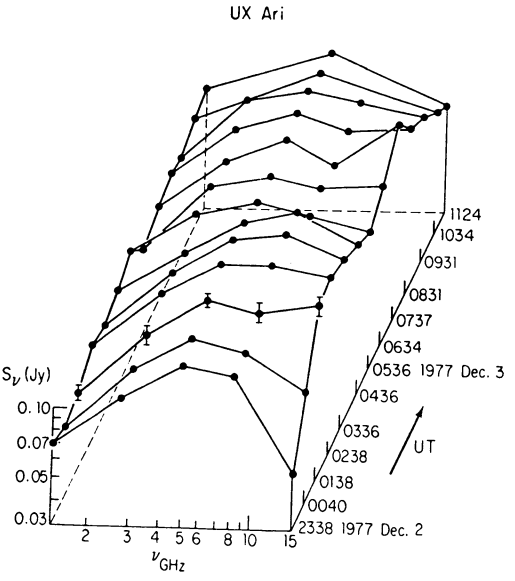

Fig. 8 - A dynamic spectrum representation of a double-peaked event in UX Ari where five frequency spectra are shown for different times during the event.

bably observed near α Sco B. The synchronous rotation forced upon later type stars in binary systems clearly increases their typical rotational velocities compared to the values in single stars (~20 km/sec), so differential rotation effects upon convective regions and surface magnetic fields will be much greater than present in comparable single stars.

REFERENCES

Altenhoff, W. J., and Wendker, H. J. 1973, 241, 27.

Baldwin et al. 1975, Nature, 241. 38.

Bath, G. T. and Wallerstein, G. 1975, Pub. Astron. Soc. Pac., 88, 759.

Brown, R. L. and Crane, P. C. 1978, Astron. J., 83, 1504.

Clark, B. G., Kellermann, K. I. and Shaffer, D. 1975, Astrophys. J., 198, L123.

Clark, T. A., Hutton, L. K., Ma., C., Webster, W., Hinteregger, C. A., Knight, C. A., Rogers, A. E. E., Whitney, A. E., Shapiro, I. I., Wittels, J. J., Niell, A. E., and Resch, G. M. 1976, Astrophys. J., 206, L107.

Davis, R. J., Lovell, B., Palmer, H. P., and Spencer, R. E. 1978, Nature, 273, 644.

Feldman, P. A. 1979a, private communication.

Feldman, P. A. 1979, IAU Circular 3366.
Feldman, P. A., Taylor, A. R., Gregory, P. C., Seaquist, E. R., Balonek, T. J., and Cohen, N. L. 1978, Astron. J., 83, 1471.
Gibson, D. M. 1976, unpublished Ph.D. thesis, University of Virginia.
Gibson, D. M. 1978, Bull. Am. Astron. Soc., 9, 600.
Gibson, D. M. 1979, Bull. Am. Astron. Soc., 10, 631.
Gibson, D. M. and Hjellming, R. M. 1974, Pub. Astron. Soc. Pac., 86, 652.
Gibson, D. M. and Owen, F. N. 1979 (in preparation).
Gibson, D. M., Hjellming, R. M. and Owen, F. N. 1975, Astrophys. J., 200, L99.
Gibson, D. M., Owen, F. N. and Hjellming, R. M. 1978, Pub. Astron. Soc. Pac., 90, 751.
Gibson, D. M. and Newell, R. T. 1979, IAU Circular 3337.
Hall, D. S. 1976, "Multiply Periodic Phenomena in Variable Stars", IAU Coll. No. 29, ed. W. S. Fitch (Reidel:Dordrecht).
Hjellming, R. M. and Blankenship, L. 1973, Nature Phys. Sci., 243, 81.
Hjellming, R. M. and Brown, R. L. 1979 (in preparation).
Hjellming, R. M., Webster, E. and Balick, B. 1972, Astrophys. J., 178, L139.
Hjellming, R. M. and Wade, C. M. 1971, Astrophys. J., 168, L115
Hjellming, R. M. and Wade, C. M. 1973, Nature, 242, 250.
Kellermann, K. I. and Pauliny-Toth, I. 1966, Astrophys. J., 145, 953.
Lovell, B. 1969, Nature, 222, 1126.
Owen, F. N. and Gibson, D. M. 1978, Astron. J., 83, 1488.
Owen, F. N., Jones, T. W. and Gibson, D. M. 1976, Astrophys. J., 210 L27.
Pooley, G. G. and Ryle, M. 1973, Nature, 244, 270.
Seaquist, E. R. 1967, Astrophys. J., 148, L23.
Spangler, S. R. 1977, Astron. J., 82, 169.
Spangler, S. R., Owen, F. N. and Hulse, R. A. 1977, Astron. J., 82, 989.
Wade, C. M. and Hjellming, R. M. 1972, Nature, 235, 270.
Walter, F., Charles, P. and Bowyer, S. 1978, Astron. J., 83, 1539.
Woodworth, A. and Hughes, V. A. 1973, Nature Phy. Sc., 246, 111.
Zeilik, M., Feldman, P. A. and Walter, F. 1977, Sky and Telescope, 57, 132.