Dick,

This is the paper which George Dulk thought should be circulated as an AT document. I said we should check with you first. Is this OK, and if so, should it be in the memo series, file notes, or whatever.

Joan

George has already given a copy to Slee, Nelson (and you)

John,
This should go in the Mem. series, 10.1.
Dick.

A.T. File

FILE COPY

AT/10.1/030

GAD:28 APR 83

CONSIDERATIONS FOR SOLAR AND STELLAR OBSERVATIONS WITH THE AUSTRALIA TELESCOPE

(revision of 7 April 1983)

Revision of 7 April 1983

CONSIDERATIONS FOR SOLAR AND STELLAR OBSERVATIONS WITH THE AUSTRALIA TELESCOPE

George A. Dulk

Over the last few years, the VLA and, to a lesser extent, Westerbork, have been used by a number of groups to observe the Sun and stars. I have used the VLA myself on about 6 occasions to observe the Sun and on about 3 occasions to observe stars. Here I will attempt to summarize some results of the observations and to indicate where the radio data have had the most impact.

SOLAR FLARES

It is astounding to realize that, despite a century of study, the basic process of energy release in solar flares remains largely unknown. Lack of accurate observations of flare locations has severely hindered theorists. Probably the most important recent result was the attainment of high resolution pictures of flares by the VLA, especially the pictures made during the impulsive flares when the energy release is the fastest and large fluxes of microwaves and hard X-rays are produced. Previously unknown was the location of the flaring volume relative to the magnetic fields of the active region. The VLA conclusively showed that the microwaves emanate from regions straddling the centers of one or many magnetic loops, an important point being the oppositely circularly polarized edges of the sources, to ~50% (see Figure 1). The source sizes are unexpectedly small, ~3" at 15 GHz, 10" at 5 GHz and 30" at 1.4 GHz. The variation of source size with frequency, emphasized by simultaneous two-frequency observations, shows that the flare volumes are distinctly inhomogeneous, with the strongest field and highest energy electrons being confined to rather small cores. These recent findings, augmented by spacecraft observations that hard X-rays emanate mainly from footpoints of magnetic loops, form one of the main pillars for the new theories of flares now being developed.

The VLA and Westerbork have limitations relative to the AT either in time resolution, frequency resolution or frequency coverage. Of course they have advantages in other characteristics. An example of an important study possible only with the AT is the (1D) imaging of source of short (1 to 10 ms) temporal structure at high frequencies (> 30 GHz). These short pulses may represent the elemental energy release events in a flare; one theory suggests that all flares result from the superposition of myriads of such mini-events. With the AT one might measure both the spatial separation from one mini-event to another and the size of the envelope of mini-events.

SOLAR MASERS

A few years ago a fascinating new kind of burst was discovered in the frequency range of about 0.6 to 3 GHz. Called microwave spike bursts, they are very short (~1 ms rise times), very intense ($T_B > 10^{12}$ K) and highly circularly polarized (to 100%). An example is shown in Figure 2.

We now believe that the spike bursts are examples of a maser process that is common in astrophysics but which remained unrecognized until after 1979, a process that now is the favored candidate to explain the terrestrial kilometric radiation, Jupiter's and Saturn's decametric radiation, solar microwave spike bursts, flare star bursts, and bursts from binary stars such as RS CVn's and AM Her type cataclysmic variables (see below). It is interesting that the first (but incomplete) theory for the relevant maser process was developed in Sydney by Richard Twiss in 1958, but applied by him to solar Type I bursts which, we now know, are due to another mechanism. The maser operates at the electron gyrofrequency and low harmonics in low density plasmas, i.e. where the gyrofrequency is higher than the plasma frequency. The pump for the maser is partial precipitation of electrons in magnetic flux tubes. This creates a vacuum in the part of velocity space where, in equilibrium, electrons of small pitch angle would exist. These "loss cone distributions" naturally occur in many magnetic structures. It is suggested that the observed solar and stellar radiation is due to a maser operating at the second harmonic of the gyrofrequency, but that most of the maser energy develops at the fundamental, is trapped, and heats the coronal plasma. This is the only known example in astrophysics where it is believed (by some) that radio waves are important energetically.

To now, no microwave spike bursts have been unambiguously observed with high spatial resolution, although two groups are proposing to the VLA to observe them, and one marginal detection of a small structure (possibly a spike burst) has been claimed by Kuijpers et al. from an European VLB experiment. The AT, with the Siding Springs and Parkes aerials, would be a powerful instrument to elucidate their properties. One could observe at various frequencies in the range ~0.6 to ~3 GHz, determining sizes to ~0.1" or 80 km on the Sun, position in 1D to about 3", and measuring polarization. With appropriate processing of the data, bandwidth could be measured (individual spikes should have a bandwidth of about 1%, or about 10 MHz at 1 GHz). It would be useful to be able to observe simultaneously at two frequencies spaced a factor of 1.5 or 2 apart in order to search for harmonic structure (1st vs. 2nd harmonic, 2nd vs. 3rd etc.). Measurement of all Stokes parameters could also be very informative; no linear polarization has heretofore been incontrovertibly detected on the Sun, but might exist in spike bursts.

SOLAR MAGNETIC FIELDS

Within the solar corona the properties of the magnetic field are largely unknown. Electric currents undoubtedly exist and alter the structure which, in their absence, can be derived from photospheric magnetograms. To the present time, radio observations are the major probe of field strengths and they have given important information of their structure, particularly above active regions. By observing at successively lower frequencies, one can sample the field at successively greater heights. Impressive results have started to come from the VLA, but the VLA is limited in the number of frequencies available. Also the circular polarization purity is less than is desirable for these studies.

STRUCTURE OF THE LOW CORONA AND TRANSITION REGION

A significant discrepancy now exists between models of the transition region and corona derived from radio and EUV observations, with the EUV data implying ~3 times higher densities (at a given temperature) than the radio. The discrepancy occurs for coronal holes, where little coronal material exists, and for normal quiet regions, where coronal material is in large scale magnetic loops. Observations at frequencies from 327 MHz to about 3 GHz could help to clarify the reasons for the discrepancy. Work on the problem will undoubtedly be done with the VLA during the next few years, but the small number of frequencies available and the circular polarization impurity will be handicaps.

SOLAR DIAMETER AND OSCILLATIONS

Using the Owens Valley interferometer at ~100 GHz, Hurford et al. recently demonstrated that, because of the sharp gradient of brightness at the limbs, the solar diameter could be measured with a precision of a few milliarcseconds. With that measurement they were able to derive the radio emitting properties of spicules, jets of material rising from and falling back onto the solar surface. An obvious extension is to measure the diameter as a function of frequency and do look for time variability over periods of minutes to days. It might not be possible to detect any periodic variability at radio wavelengths, but if it is, the observations could prove to be particularly valuable as a probe of the solar interior: various hydrodynamic wave modes arising deep in the Sun reveal themselves in the atmosphere. Their study, "solar seismology", is of great current interest, with important implications, for all of stellar evolution. (NASA is now considering an "urgent" new spacecraft to be devoted to the subject.)

STELLAR CHROMOSPHERES, CORONAE AND ACTIVITY

Over the past few years many astronomers were greatly surprised to find that coronae exist on a wide variety of stars, quite unexpectedly for stars in certain parts of the HR diagram. Most evidence came from X-ray observations, especially by the Einstein observatory. Meanwhile, solar studies had demonstrated that X-rays from the quiet corona arise almost entirely in magnetic loops, and that a necessary and perhaps sufficient condition for coronae are magnetic fields. Thus was born the "solar physics of stars". To date, quiescent emission from several stars has been detected at radio wavelengths and the measurements do not always agree with models derived from the X-ray data. For example, for the star X1 Orionis the radio data require the presence of higher temperature material (several x 10^7 K) or a more extended corona (several stellar radii) than one would have expected from X-ray data alone.

As from the Sun, the emission from stellar coronae undoubtedly varies on several time scales, from day to day as active regions and starspots are born and die or rotate into and out of view, and from year to year in an activity cycle.

To elucidate their properties, most importantly the magnetic fields, observations are needed with high sensitivity, high polarization purity and good spectral coverage (frequencies separated by a factor of 2:1 or less).

FLARE STARS

Flares are common on certain kinds of stars, especially M dwarfs, and are seen at wavelengths from X-ray to radio. The energies of the flares sometimes exceed those of their solar counterparts by several orders of magnitude. Several different emission mechanisms may be important at radio wavelengths--plasma, gyrosynchrotron and maser--and they can be distinguished by their spectra, polarization and time variations. Figure 3 shows the time variability of one such stellar flare recorded at the VLA; interestingly, the quiescent emission arose from one star of a widely separated pair of dMe stars and the burst arose from the other. Some believe that this intense, highly circularly polarized burst is due to the electron-cyclotron maser mechanism mentioned earler, but this is a new idea that has not been accepted by all.

Studies of flare stars are proceeding at the VLA. It has many advantages for the studies but is somewhat handicapped in obtaining spectra by its 3:1 frequency separations (most bursts undoubtedly have a narrower frequency range) and by the impurity of its circular polarization measurements. It is generally accepted that magnetic energy is at the root of these flares, but only in the radio range does the field strength strongly affect the emission. Thus accurate measurements of all Stokes parameters are highly desirable so that properties of the field can be derived.

FLARE STARS AND STELLAR EVOLUTION

An important discovery, made by Haro and Morgan in 1953, is that flares are common in T Tauri stars and stellar associations, implying that flare processes are stronger in the younger stars, and that flaring may be important to the process of stellar formation and development. It may even be true that in the early stages of their lives, all stars pass through a stage of flare activity (Gurzadyan 1980). For example, of 175 T Tauri stars in the Orion association with H emission lines, 28 have flare-like activity at visible wavelengths on time scales <30 min. Altogether 325 stars in Orion, within spectral classes K0 to M3, are known to flare. In the Pleiades 469 stars are flare stars.

It would be surprising if radio emission did not accompany the optical activity in many of these stars and associations. Many undoubtedly have magnetic fields and fast electrons. For example, one theory of the origin of visible flare radiation from cool stars is the conversion of (the plentiful) IR photons to visible photons by inverse Compton scattering by nonthermal electrons. A search for radio emission at 150 and 408 MHz from the Orion association was made more than a decade ago by Slee and Higgins (1971) and they obtained several convincing detections of surprisingly powerful bursts. To my knowledge, no one has searched at higher frequencies with an instrument as powerful as the VLA now is and the AT will be, with the capability of measuring polarization and pinpointing which star is emitting. Because the distance to most of the stellar associations is some 30 times farther than to typical flare stars like UV Ceti, the flux density is down by a factor of 1000, and thus undetectable if the flares are comparable in intensity. However, the bursts reported by Slee and Higgins and the outburst on AM Her (see below) were 10 to 1000 times more intense than is typical of flare stars. Thus it should be expected that radio bursts can be detected from some nearby T Tauri stars and stellar associations.

It is noteworthy that, because radio emissions generally depend on the characteristics of the magnetic field, its detection from young stars should be expected and important: expected because magnetic fields and hence nonthermal radio bursts are likely to exist near newly formed stars, and important because magnetic fields probably play a crucial role in the initial stellar evolution (e.g. the spinning down of the proto-Sun) and radio methods are perhaps the only way of detecting the fields and deriving their properties.

STELLAR WINDS

As with coronae, stellar winds are now known to flow from a wide class of stars; in fact most stars either have a wind or a hot corona. A coup for radio astronomy in recent years has been the use of radio flux measurements for accurate derivation of mass loss rates, free from most of the uncertainties that plague UV, optical and IR observations. The resulting picture of mass losses is interesting in itself because of the new insight into hydrodynamics coupled with radiation, and it has strongly affected certain aspects of stellar evolution (the time scale for mass loss is, for some stars, comparable with the time scale for nuclear burning). Some aspects of interstellar physics and star formation are affected because, associated with the stellar mass losses, are interstellar mass gains and shock waves. Temporal changes in mass loss rates from stars may well be important, but to now there is little information on them; however, they should be prominent in radio flux measurements.

CLOSE BINARY STARS

AM Herculis, the prototype of the class of magnetic cataclysmic variable stars, has now been detected with the VLA. The primary star of the system is a white dwarf with a surface field of about 10^7 gauss, sufficiently strong that the secondary, a red dwarf, is embedded in the magnetosphere. The suggested model for the quiescent radio emission has ~300 keV electrons trapped in the magnetosphere and emitting gyrosynchrotron radiation, with the electrons possibly energized in a way analogous to Io's effect as a unipolar inductor in Jupiter's magnetosphere. The quiescent emission is visible in Figure 4 (top panel).

Very recently an outburst of radio emission was serendipitously discovered on AM Her (Figure 4). The rapid time variability, high brightness and high circular polarization imply a coherent radiation mechanism, possibly an electron-cyclotron maser of the kind discussed above. The location of the source is uncertain but most likely it was on or near the red dwarf. If so it implies the existence of a magnetic field on the red dwarf and thus the likelihood of magnetic interactions between the fields of the two stars. The previously unexplained variations in X-ray, UV and optical activity on time scales of months could result from such interactions modulating the transfer of matter from the red to the white dwarf.

The spectrum of the outburst is entirely unknown; it was detected at 5 GHz but not at 15 GHz when the latter was in use during the gaps in the central panel of Figure 4. This underscores the need for simultaneous measurements at two frequencies spaced a factor of 2:1 or less apart; less desirable but still useful would be the ability to switch rapidly between the two frequencies. Measurements of circular polarization are also extremely important.

RS CVn's represent another interesting type of close binary star. As shown in Figure 5, they have a smoothly varying component of low polarization and a more rapidly varying component with strong circular polarization. The former is most evident in Figure 5 at 8.1 GHz and is probably due to incoherent gyrosynchrotron radiation. The latter is evident only at 2.7 GHz and is attributable to the electron cyclotron maser. VLB measurements have indicated a source size of $\sim 10^{11}$ cm (probably pertaining to the slowly varying component),/ which is approximately the separation of the two stars. Strong magnetic fields, giant starspots and activity cycles are inferred in RS CVn systems. Either mass transfer or magnetic field interactions between the two stars (see Figure 6) may account for the intense activity observed.

Radio emission of high brightness has reportedly been detected from another class of variable stars, the dwarf novae. This might also have resulted from the electron cyclotron maser.

Desirable observations for RS CVn's and dwarf novae include those mentioned for the AM Her stars and, in addition, VLB measurements from Culgoora to Tidbinbilla.

EXPECTED NUMBERS OF STARS DETECTABLE WITH THE AT

Here I give rough estimates of the number of stars of several kinds that should be detectable with the AT. At the outset I emphasize the importance of making the sensitivity as high as possible, for example by enlarging the AT bandwidth to 256 or 512 MHz and/or by incorporating Siding Spring and, especially, Parkes, with as large a bandwidth as possible. The reason has to do with the number of stars detectable at the desired S/N ratio given an integration time fixed at ~1 to 10 s by the time variability of the emission. Assuming that Tsys is the minimum practical, then the S/N could be improved by about a factor of two by incorporating the large aperture of Parkes with the same bandwidth as at Culgoora (with interesting exceptions stars would all be point sources for Parkes-Culgoora), and could be improved by a factor of 1.4 to 2 by doubling or quadrupling the bandwidth.

Because stellar sources are relatively close to the solar system, less than a few hundred parsec, their number increases as Dlim^3, where Dlim is the limiting distance for a source to be detectable with the given S/N (say 5:1) and integration time, say 10 s. On the other hand, the flux density goes as Dlim^-2. Therefore the number of detectable sources N goes as

$$N \propto A_{eff}^{1.5} \; B^{0.75}$$

Hence doubling the bandwidth would allow 68% more stellar sources to be detected and quadrupling it would allow 2.8 times more to be detected. Similarly, inclusion of Parkes with full bandwidth would allow 2.8 times more sources to be detected.

Flare Stars: Typical flux densities of flares on stars about 10 pc distant are 10 mJy at 5 GHz. The AT of "standard specification" (128 MHz bandwidth and 10 MHz bandwidth Parkes-Culgoora) will have rms ~ 0.7 mJy with 10 s integration, and could obtain a 5 sigma detection of a typical flare on a star at Dlim = 17 pc. It is estimated that there are 38 flare stars within 10 pc. Thus there should be about 180 detectable flare stars for the "standard" AT. If the bandwidth were doubled to 256 MHz the number would increase to about 300, and if quadrupled to 512 MHz the number would be about 500.

At lower frequencies, say 0.4 GHz, the flux density of detected flares is about 0.5 to 5 Jy. Although these are relatively high values, given the higher system temperature, lower bandwidth and increased confusion at the lower frequency, the number of detectable flare stars should be much the same as above. Comparison of characteristics of flares at high and low frequencies is important to establish whether, as is the case for the Sun, gyrosynchrotron emission and electron-cyclotron masers dominate at frequencies > 1 GHz while plasma radiation dominates at < 1 GHz.

Close Binary Stars: Stars such as AM Herculis type binaries are much rarer than flare stars, the closest being ~100 pc distant. The outburst detected on AM Her was ~10 to ~100 times more energetic than is typical of stellar flares. With considerable uncertainty it can be estimated that similar outbursts on 5 AM Her type stars would be detectable with the "standard" AT, 8 if the bandwidth were doubled, and 14 if quadrupled.

Stellar Associations and Clusters: Outbursts such as that on AM Her could be detected at a distance of 170 pc with the "standard" AT, 200 pc if the bandwidth were doubled and 240 pc if quadrupled. There are roughly 16, 21 and 22 associations and open clusters within these distances respectively.

Quiescent Radio Emission from Stars: While a large number of stars are known to emit X-rays more or less steadily, to my knowlecge only a half dozen or less have been detected at radio wavelengths, although searches are being or have been made for others. The flux densities of the detected stars run from about 0.5 to 5 mJy and the distances from about 2 to 100 pc. Because the ratio of outburst to quiescent flux is one to two orders of magnitude and the ratio of integration times possible is two to four orders of magnitude, the number of detectable quiescent radio emitters should be roughly the same as the number of flare stars.

DESIRABLE CHARACTERISTICS OF THE AUSTRALIA TELESCOPE FOR SOLAR AND STELLAR OBSERVATIONS

FIRST PRIORITY

(1) Ability to cope with high solar fluxes, about 1 MJy (Megajansky) for the quiet Sun and up to 100 MJy for flares, while retaining accurate flux and phase calibrations, the latter presumably derived from measurements of ~1 Jy sources. Also must cope with rapid changes of flux and hence system temperature.

(2) Ability to measure all Stokes parameters accurately, especially circular polarization. Polarization accuracy should be retained over a large field, e.g. the half-power beam of the aerials.

(3) High sensitivity: rms < 1 mJy in a 1 s observation.

(4) High time resolution: <10 ms.

(5) Ability to work at two frequencies simultaneously or, at least, in rapid sequence (~1 s). The spacing between available frequencies should be at most 2 to 1; exactly 2 to 1 would be valuable for the purpose of examining harmonic structure, if it exists. A good set of frequencies would be:

- 0.3 to 0.4 GHz: study of decimeter bursts from the Sun and stars; also the quiet Sun.
- 0.6 to 0.8 GHz: decimeter bursts from the Sun and stars; quiet Sun; electron-cyclotron masers.
- 1.4 to 1.8 GHz: decimeter bursts from the Sun and stars; quiet Sun; electron-cyclotron masers.
- 2.5 to 3.0 GHz: solar and stellar flares; magnetic fields in active regions; high end of solar masers; stellar masers; stellar chromospheres and coronae.
- 4.5 to 5.0 GHz: solar and stellar flares; magnetic fields in active regions; stellar masers; stellar magnetospheres; stellar chromosheres and coronae; mass loss from stars.
- 9.0 to 10. GHz: solar and stellar flares; magnetic fields in active regions; high end of stellar masers?; mass loss.
- 20. to 22. GHz: solar and stellar flares; solar diameter and oscillations; stellar magnetospheres; mass loss.
- 40. to 44. GHz: solar and stellar flares; solar diameter and oscillations; stellar magnetospheres.
- 80. to 88. GHz: solar flares; solar diameter and oscillations; stellar magnetospheres?

SECOND PRIORITY

(1) Ability to measure the spectrum within a given band, e.g. from 1.3 to 1.8 GHz. Could the spectral line system do this? Or autocorrelation processing?

(2) Utilization of Parkes and sometimes Tidbinbilla with Siding Springs and Culgoora, with all of the capabilities listed above.

(3) Ability to change pointing rapidly (~1 s) between two positions separated by a degree or so (e.g. from one solar limb to the other, or from one active region to another).

FIGURE CAPTIONS

Figure 1. Pictures showing the location of 15 GHz radio sources relative to the Ha brightenings and the magnetic neutral line (line of reversal of the longitudinal component). The two pictures were taken 10 s apart, the Ha pictures at Big Bear Solar Observatory and the radio pictures by the VLA. Black and white contours represent RH and LH polarization respectively. (From Hoyng et al. 1983).

Figure 2. Time history of the 1 GHz radiation from a solar flare. The top half shows the flux density (sum of the two circular components: R+L, while the lower half shows the difference: L-R. Note the small excess of R+L which represents the (noncoherent) microwave burst that was dominant at frequencies >2 GHz. The spiky component, ~100% circularly polarized, is probably due to an electron cyclotron maser. (From S. Enome, personal communication).

Figure 3. Time history of the 4.9 GHz radiation from the dMe binary pair UV Ceti. The low level quiescent emisson in the top panel is due to UV Ceti itself while the "flare" is due to the companion. The lower panel shows the time history with 10 s resolution, demonstrating that factor-of-two variations occur within the 10 s resolution of the VLA. Note also that the burst was ~100% circularly polarized. (From Gary et al. 1982).

Figure 4. Time history of the 4.9 GHz radiation from the magnetic cataclysmic binary AM Her. The three panels show the emission on three time scales. Note that the [illegible] ~100% circularly polarized. (From Dulk, Bastian [illegible] 1983).

Figure 5. Time history of the 2.7 and 8.1 GHz radiation from the RS CVn type binary HR 1099, showing a highly [illegible] polarized outburst at 2.7 GHz but no similar outburst at 8.1 GHz. (From Brown and Crane 1978).

Figure 6. Calculated magnetic field lines within an RS CVn system based on a model of the field strengths on [illegible] two stars. The system is assumed to rotate synchronously; temporal changes in the fields of the two stars or differential rotation would cause reconnections and [illegible] possible cause of the outbursts. (From Uchida and Sakurai 1983).

Figure 1

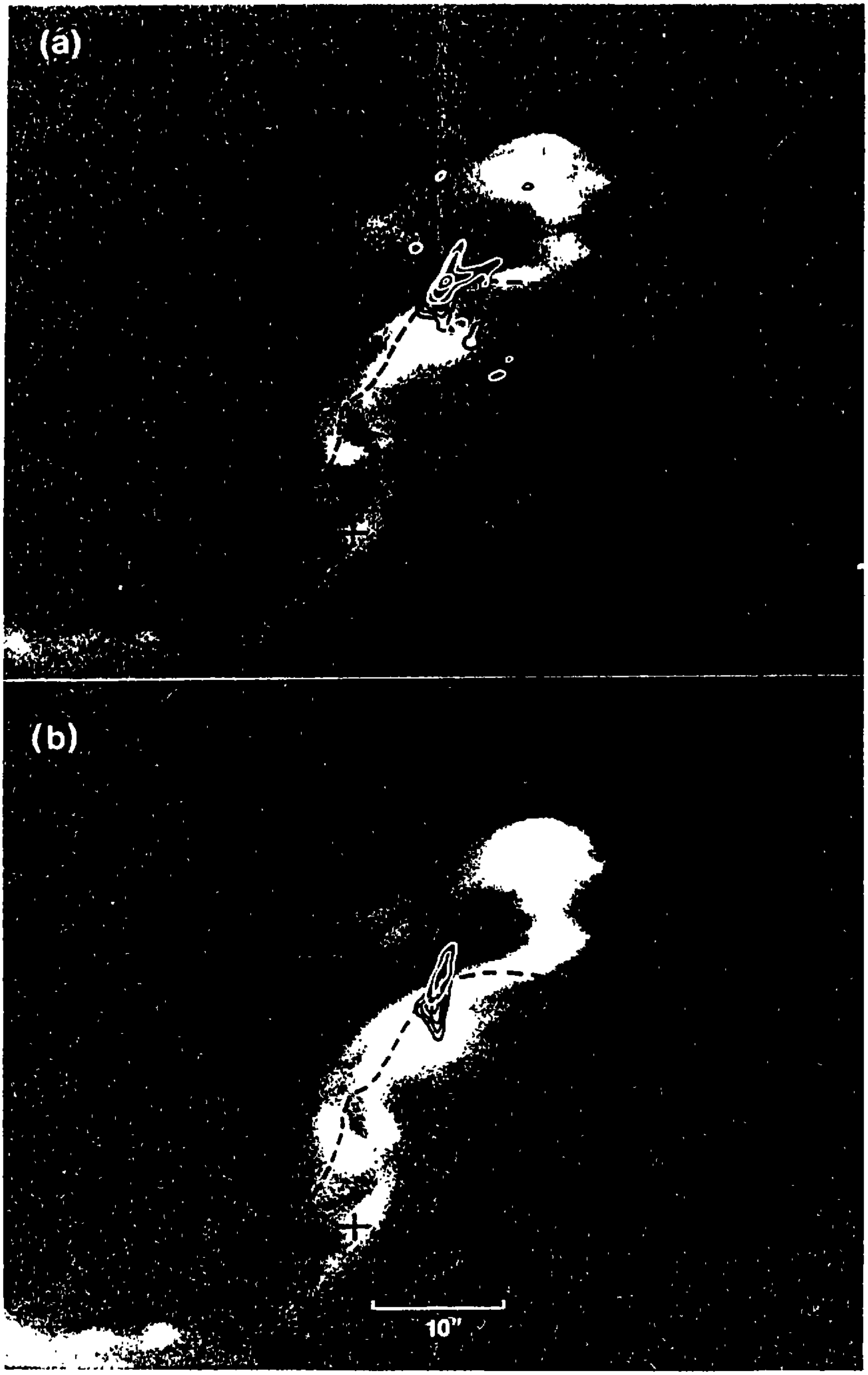


Figure 2

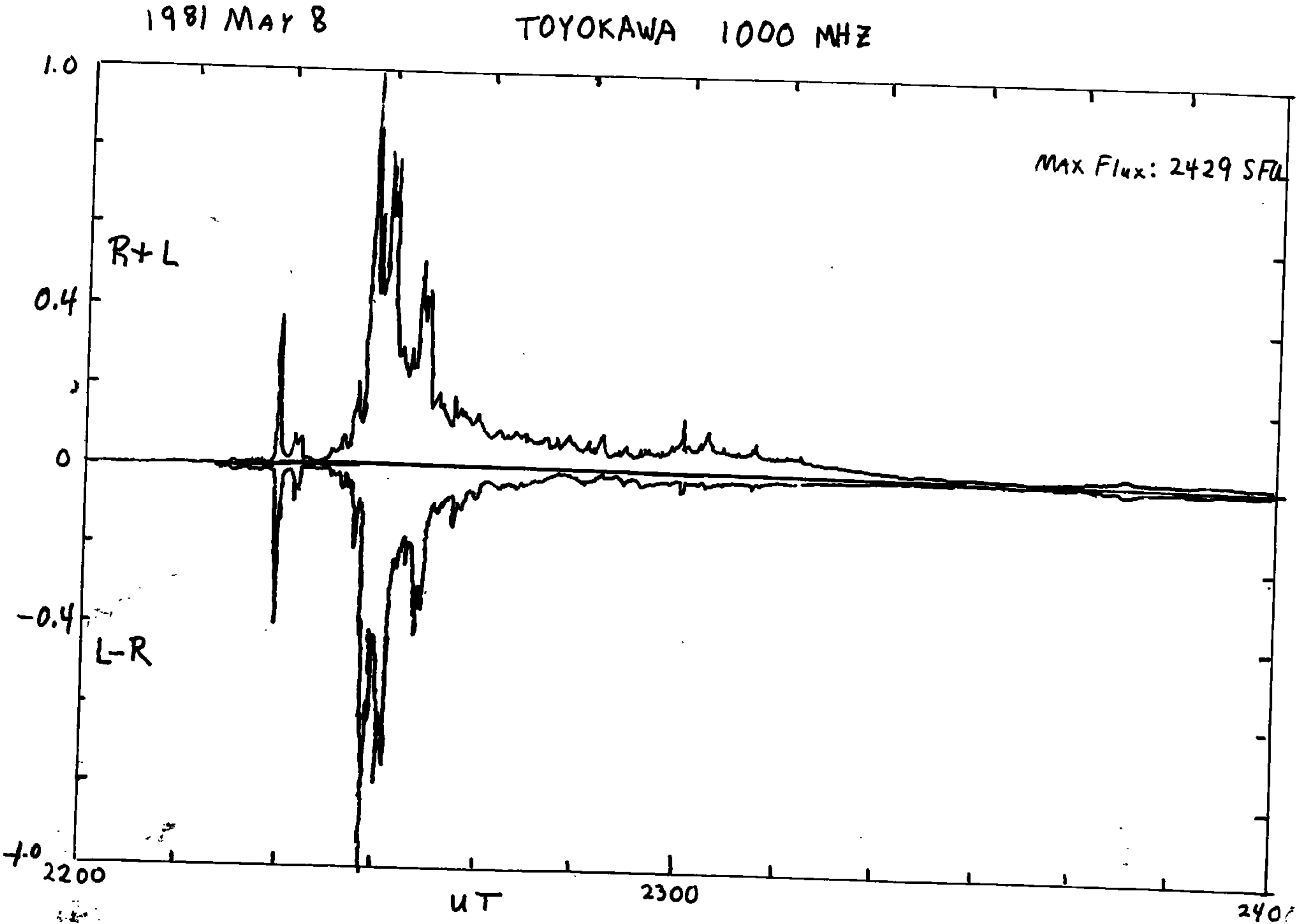

1981 MAY 8
TOYOKAWA 1000 MHZ
MAX Flux: 2429 SFU
R+L
L-R
1.0
0.4
0
-0.4
-1.0
2200
2300
240
UT

Figure 3

Gary et al. (1982)

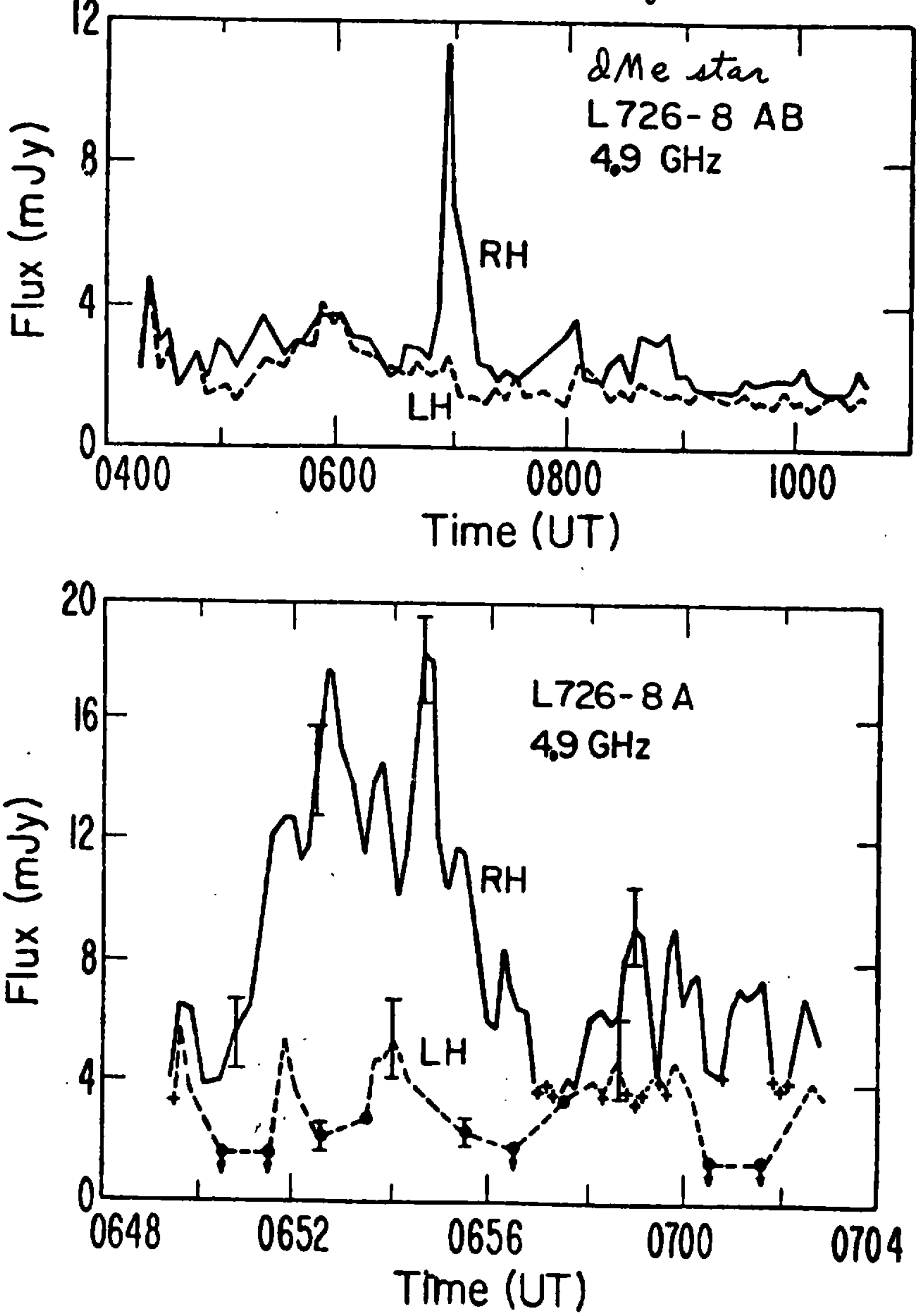


Figure 1

Figure 4

A M Herculis

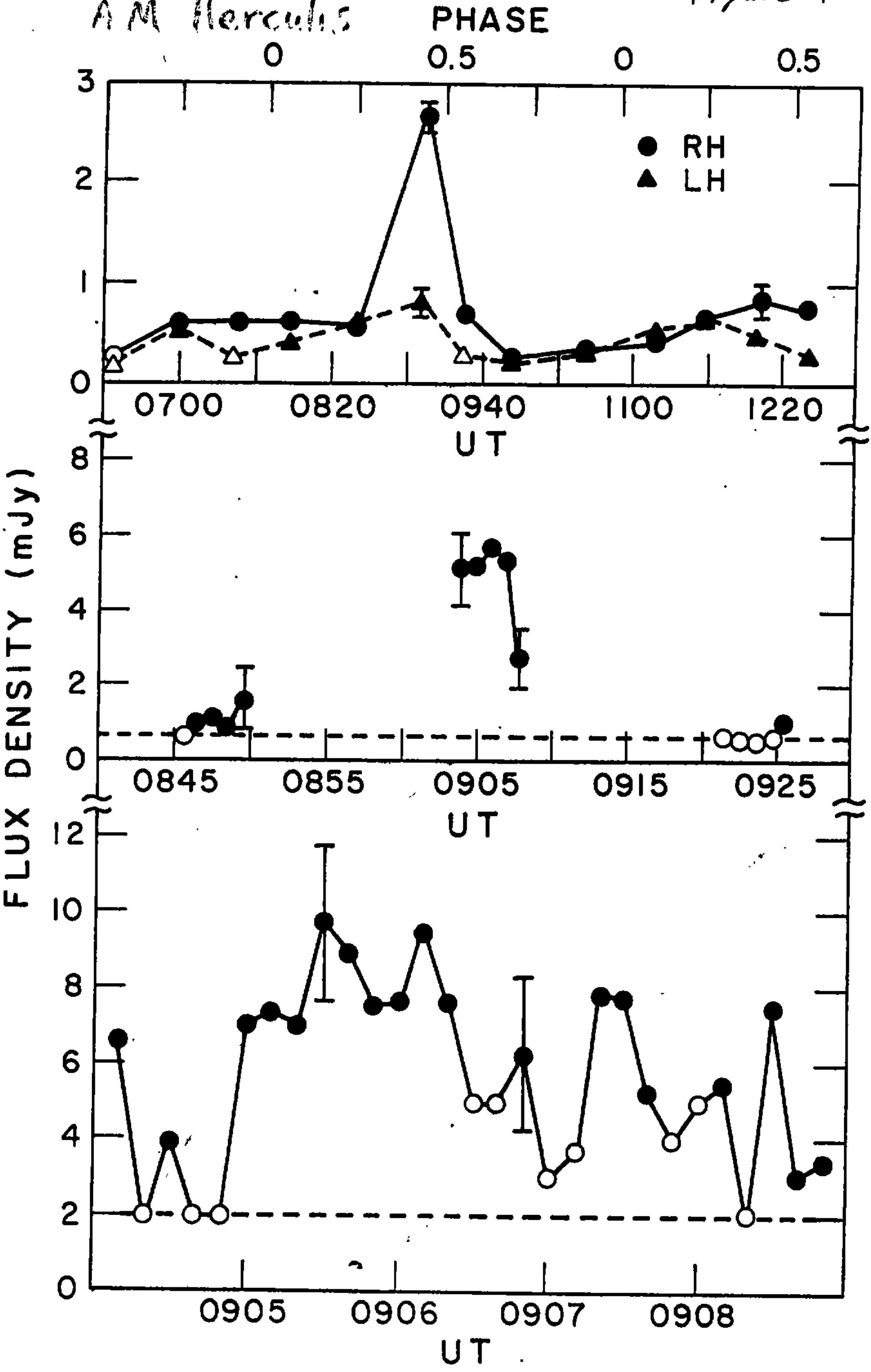
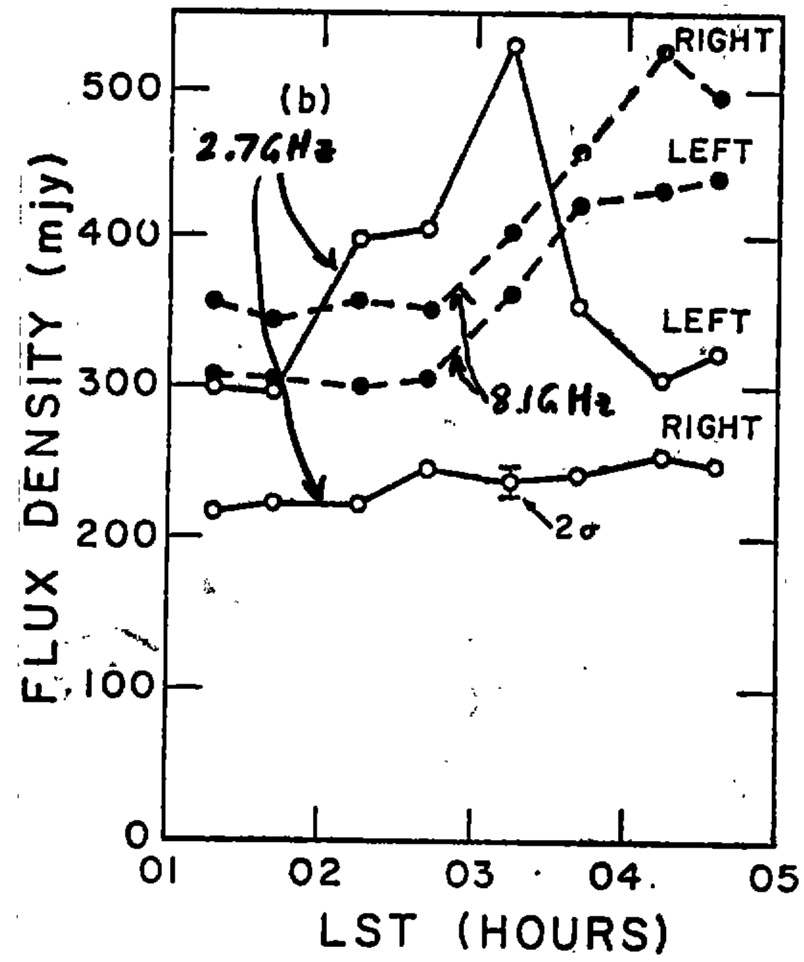


Figure 5

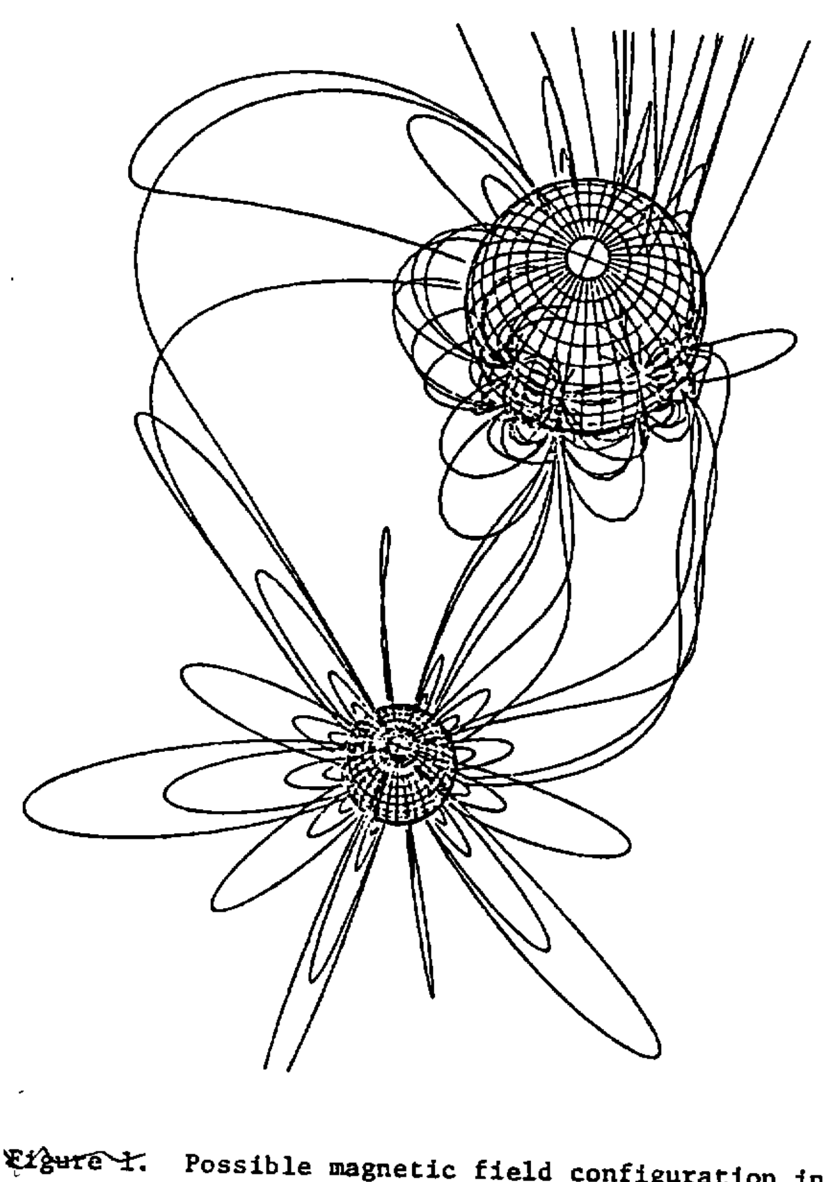
RS CVn star HR1099

Brown and Crane 1978



igure 1

Figure 6



~~Figure 1.~~ Possible magnetic field configuration in RS CVn system. For detailes, see the text.