Simultaneous optical, infrared and microwave observations of the flare star AT Mic

G. J. Nelson, R. D. Robinson and O. B. Slee *Division of Radiophysics, CSIRO, PO Box 76, Epping, NSW 2121, Australia*

M. C. B. Ashley, A. R. Hyland and I. R. Tuohy *Mt Stromlo and Siding Spring Observatories, Private Bag, Woden PO, ACT 2606, Australia*

I. Nikoloff *Perth Observatory, Perth, Western Australia*

A. E. Vaughan *Macquarie University, North Ryde, NSW 2113, Australia*

Summary. We report the first extensive observations of the binary dMe flare star AT Mic made simultaneously at optical, infrared and microwave wavelengths. The observations have failed to show decreases in infrared flux at the time of optical flares. Such decreases are expected if the inverse Compton scattering mechanism proposed by Gurzadyan is dominant during the flares. On the contrary, one large flare showed a significant increase in the K-band flux consistent with an energy spectrum which is flat, at least in the range from U to K bands. The J-band flux, however, showed no significant average change during a large number of smaller flares. These results are discussed in terms of a number of thermal and non-thermal flare models. It is concluded that the data can be best accounted for in terms of a hot ($\sim 10^5$ K) plasma flare model which produces a relatively flat energy-spectrum over a range of wavelengths determined by the temperature, density and depth of the source region. This range may therefore vary from flare to flare and from star to star. Microwave observations during a large number of optical flares indicate a variation of at least several orders of magnitude in the ratio of optical to microwave flare luminosities. This is taken to imply that different plasmas are responsible for the two emissions.

1 Introduction

Flare stars are generally red dwarfs of spectral class M. They are therefore cool stars with maximum emission in the infrared. When observed in visible or ultraviolet light they exhibit manifold increases in brightness during flares which may last up to tens of minutes (Fig. 1). However, because the quiescent emission is mainly in the infrared, the visible and ultraviolet energy in most flares represents an increase of only a few per cent in the star's total energy output.
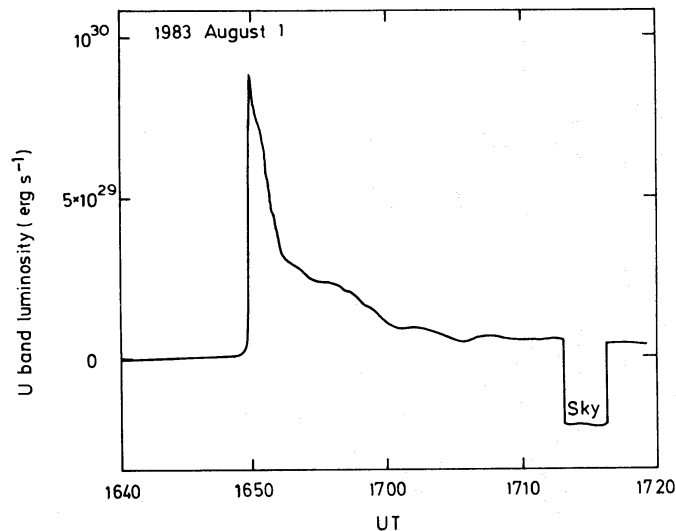
Figure 1. A large impulsive flare on AT Mic observed in *U* band with the 0.75-m telescope at Mt Stromlo.

It is therefore of considerable interest to investigate the nature of the flare emission near the peak of the quiescent spectrum in the infrared.

In most thermal (Kunkel 1970b; Kodaira 1977) and non-thermal (Grindlay 1970) theories that might be considered to explain flare star emission, a small increase in infrared emission is to be expected. On the other hand, a mechanism proposed by Gurzadyan (1980) predicts a *decrease* in the infrared emission during flares. This theory involves inverse Compton scattering of infrared photons off mildly relativistic electrons to produce visible and ultraviolet photons. During a flare produced by this mechanism a small fractional decrease in the infrared flux could be accompanied by a manifold increase in the flux at shorter wavelengths.

Table 1. Properties of AT Mic.

Right ascension	$20^h 38^m.7$
Declination	$-32°36'.6$
Spectral class of each component (Joy & Abt 1974)	dM 4.5e
Mass of each component deduced from spectral class (Allen 1973)	$0.2\ M_\odot$
Radius of each component deduced from spectral class (Allen 1973)	$0.32\ R_\odot$
Distance to star (Pettersen 1976)	8.2 pc
Separation of components (Pettersen 1976)	4 arcsec in PA 231°
Total apparent and absolute magnitude of binary system: Kunkel (1970a)	$U = 12.90,\ M_U = 13.33$
" "	$B = 11.81,\ M_B = 12.24$
" "	$V = 10.22,\ M_V = 10.65$
Present authors	$J = 5.88,\ M_J = 6.31$
	$K = 4.80,\ M_K = 5.23$

The existence of electrons with energies suitable for inverse Compton scattering was confirmed by the detection of non-thermal radio emission at 5 GHz accompanying an optical flare on AT Mic (Slee *et al.* 1981). Similar microwave flares have now been detected on several flare stars (Fisher & Gibson 1982; Slee *et al.* 1984). Thus inverse Compton scattering must occur to some extent during flares which are accompanied by microwave emission. Whether it is the dominant mechanism responsible for the visible and ultraviolet flare emission is another matter. In an attempt to shed light on this question we report the first extensive simultaneous observations of the binary flare star AT Mic (Table 1) at optical, infrared and microwave wavelengths. No attempt has been made in any of the observations to resolve separately the two members of the binary system. They are similar and both are assumed to produce flares.

2 Observations

The results of two separate observing sessions are reported here. In the first session of three nights in 1982 July, various flare stars were observed photometrically with the 3.9-m Anglo–Australia telescope simultaneously in K band and in either U band or B band. Only the observations of AT Mic will be reported here. In the second session of three nights in 1983 August, photometric observations of AT Mic were made simultaneously with the 1.9-m telescope at Mt Stromlo in J band, the 0.75-m telescope at Mt Stromlo in U band and the 0.6-m telescope of the Perth Observatory in B band. In addition, the radio emission from the star was monitored at 5 GHz with the 64-m Parkes radio telescope and at 843 MHz with the 1.6-km Molonglo synthesis telescope.

The various optical and infrared photometric observations were recorded with integration times ranging from 1–10 s. Before examining these data for the presence of flares, the observations with higher time resolution were averaged over longer periods. The resulting data from all sources then had integration times in the range 7–10 s. Flares were listed only if they resulted in an increase in brightness of 3σ and persisted for at least three samples. In fact the average FWHM for the observed flares was >2 min, so a much more complete list of weaker flares could in principle have been obtained with longer integration times. Nevertheless, for comparison with the infrared observations the stronger flares are of most interest. When both U and B observations were in progress simultaneously, a flare detected easily in U was occasionally accompanied by a flare in B which was weaker than the above criterion. In these cases the magnitude of the B flare was deduced using appropriately longer integrations.

At 5 GHz, integration times of ~2 min were required to achieve confusion-limited results. Details of these observations which involve dual beams alternately placed on and off the star are given by Slee *et al.* (1984). When a 5-GHz burst was detected without an accompanying U-band flare, the U-band data were re-examined with longer integration times in order to detect any faint, long-duration flares.

The 843-MHz flare observations were made with the 1°.6×43 arcsec fan beam of the Molonglo synthesis telescope using a time constant of 96 s. A total of 12 hr of data was recorded on 1983 August 2. All data were inspected for the presence of flares and were then combined to produce a synthesized beam of ~40-arcsec beamwidth in an attempt to detect quiescent emission or weak, very-long-duration flare emission.

Table 2 summarizes the flares observed at the various wavelengths. No entry in a column indicates that no observations were made at that wavelength. Upper limits (3σ) are shown where observations were made but no significant flare was detected. All parameters are measured at the peak of the flare. Δm is the change in apparent magnitude of the star at the given wavelength; U_f and B_f are the apparent magnitudes of the flare emission alone and M_{U_f} and M_{B_f} are the corresponding absolute magnitudes. Values of M_{U_f} and M_{B_f} in brackets are not observations but

Table 2. Flares observed on AT Mic.

Date (UT)	Δm_U	Δm_B	Δm_J	Δm_K	M_{U_f}	M_{B_f}	$U_f - B_f$	Flux density 5 GHz (mJy)	843 MHz (mJy)
1982 July 10									
140950		0.05		<0.003	14.85	15.55			
141210		0.15		<0.003	13.59	14.29			
163240		0.48		0.005	12.17	12.87			
172740		0.07		<0.003	14.45	15.15			
173700		0.08		<0.003	14.32	15.02			
185750		0.05		<0.003	14.95	15.65			
1982 July 11									
130540	0.37			<0.003	14.31	(15.01)			
135220	0.43			<0.003	14.10	(14.80)			
135720	1.10			<0.003	12.72	(13.42)			
142130	0.32			<0.003	14.49	(15.19)			
142340	0.38			<0.003	14.28	(14.98)			
162955	0.67			<0.006	13.50	(14.20)			
1983 Aug. 1									
125510	0.50	<0.006			13.92	(14.62)		<11.5	
132848	0.34	<0.006			14.40	(15.10)			
140824	0.14	<0.006			15.51	(16.21)			
164948	1.72	<0.006			11.84	(12.54)		<11.5	
174149								23.5	
1983 Aug. 2									
104218	<0.16				>15.3			11.6	
122529	<0.16		<0.006		>15.3			13.5	
130036	0.63				13.58	(14.28)		<11.5	<120
142324	0.56		<0.006		13.74	(14.44)			<210
1983 Aug. 3									
094236	0.29				14.60	(15.30)		<11.5	
111724	0.84		<0.006		13.15	(13.85)		<11.5	
111912	0.85		<0.006		13.14	(13.84)		<11.5	
122512	0.33		<0.006		14.46	(15.16)		<11.5	
131800	0.30	0.11	<0.006		14.56	14.64	-0.08		
140412	0.83	0.22			13.18	13.85	-0.67		
141012	1.25	0.35	<0.006		12.48	13.32	-0.84		
142136	1.10	0.27	<0.006		12.70	13.63	-0.93		
152248	0.32	0.08	<0.006		14.49	15.00	-0.50	<11.5	
153000		0.41	<0.006		(12.41)	13.11		16.5	
163712	0.36	0.07	<0.006		14.33	15.25	-0.92	<11.5	

have been derived from the relationship $U_f - B_f = -0.7$, which is discussed in Section 4.2. They have been included so that all of the observed flares can be categorized by a common parameter.

3 Results and discussion

Because of the diverse nature of the observations reported here, we will first discuss the optical observations in terms of various proposed flare models. The microwave and infrared observations will then be presented and discussed against this background.

3.1 FLARE INCIDENCE

A total of 32 flares are indicated in Table 2. Twenty-nine of these were detected in *U* or *B* in a total observing time of 39.3 hr. The remaining three events were detected only at 5 GHz. This flare incidence appears to be considerably less than reported by Kunkel (1970a, 1973) for the epochs of 1967.72 and 1969.70. He reported a total of 78 *U*-band flares in 27.6 hr. Fig. 2 shows the incidence
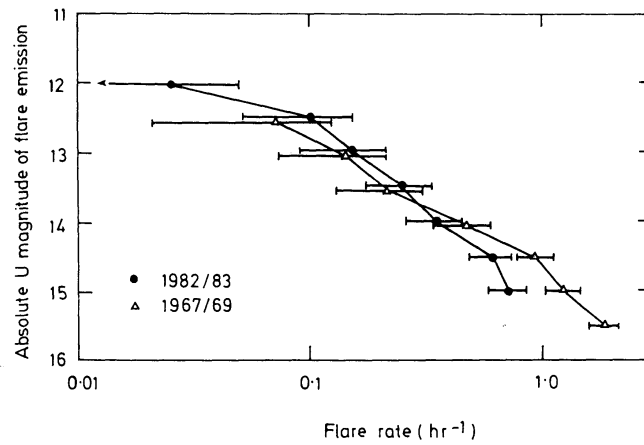
Figure 2. The occurrence rate for flares on AT Mic brighter than a given absolute U magnitude. The magnitude is for the flare emission alone and does not include emission from the quiescent star.

of flares brighter than a given absolute U magnitude for epochs 1967.7/1969.7 and 1982.5/1983.6. The error bars have been assigned on the assumption that flares occur randomly in time. The apparent decrease in the incidence of weak flares between the two epochs is probably a result of the different sensitivities and selection criteria used. On the other hand, there seems to have been no significant change in the incidence of large flares, which are the ones most likely to be associated with detectable microwave or infrared flares.

3.2 FLARE COLOUR

Of the 29 optical flares listed in Table 2, 22 were observed in U and 13 in B. No U observations were made during seven of the B flares, but for six events both U and B observations are available. To allow all flares to be categorized by their U magnitude, a relationship between U and B magnitude is required. The existence of such a relationship has been reported for other
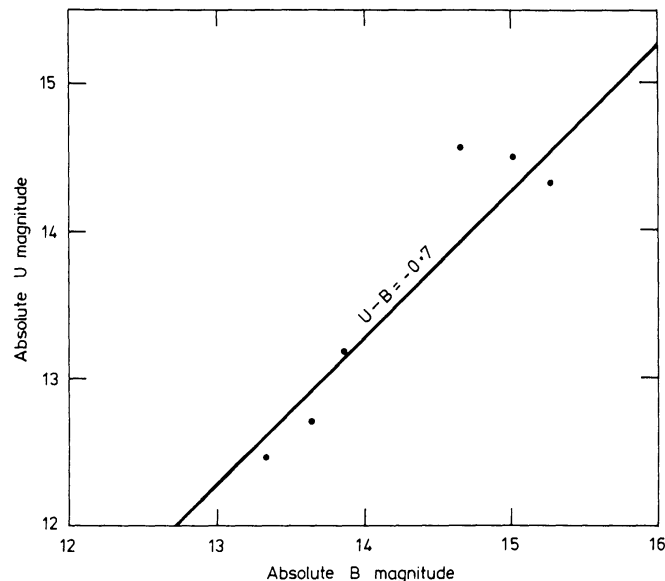

Figure 3. The absolute magnitude at flare maximum for six flares observed simultaneously in U and B bands. The emission from the quiescent star is not included so the magnitudes are for the flare alone. The average of U–B for the flares is −0.7.

stars but not specifically for flares on AT Mic. Gurzadyan (1980) summarized $U_f - B_f$ observations for flares on 10 flare stars of UV Ceti type. The average values range from -0.48 ± 0.18 for BD $+55°1823$ to -1.14 ± 0.25 for Wolf 424, and the mean for all 10 stars is -0.88 ± 0.21. The six available values of $U_f - B_f$ for AT Mic (Table 2) are plotted in Fig. 3. The weighted mean is -0.7 ± 0.3. This is slightly smaller than the mean quoted above for flares on other stars, but the uncertainty is comparatively large, partly because of the small samples size. Using the relation $U_f - B_f = -0.7$, we have assigned U magnitudes to the seven flares in Table 2 which were only observed in B.

It is worth discussing at this stage the significance to various flare models of the observed value of $U_f - B_f$. Models in which the emission has a thermal origin are discussed first.

3.3 BLACK-BODY EMISSION (10 000 K)

A naive flare model might assume blackbody radiation from a heated region of the photosphere. A blackbody at a temperature of $\sim 10\,000$ K emits radiation with $U - B \simeq -0.7$. Such a source also produces some infrared emission ($B - K \simeq 0.5$). Thus, with this model and using parameters from Table 1, a moderately large flare on AT Mic with $\Delta m_U = 1.5$ would have $\Delta m_B \simeq 0.5$ and $\Delta m_K \simeq 0.0015$. These parameters are shown in Table 3 for comparison with other flare models.

3.4 HOT PLASMA (25 000 K) PLUS PHOTOSPHERIC HEATING

In practice the flare emission is unlikely to be blackbody (i.e. photospheric in origin). A more likely model for a thermal flare presented by Kunkel (1970b) assumes emission from an optically thin layer of recombining hydrogen. This is essentially the mechanism generally accepted for solar flares. In this case $U_f - B_f$ depends both on temperature and on the optical depth in Hα. Thus $U_f - B_f = -0.7$ does not uniquely determine the temperature of the flare. In his model, Kunkel restricted himself to temperatures around 25 000 K for consistency with observations that showed flare spectra with large Balmer jumps. At this temperature an optical depth in Hα of 50 produces

Table 3. Optical and infrared properties of stellar flare models.

Model	$U_f - B_f$	$B_f - V_f$	$B_f - K_f$	Δm_U	Δm_B	Δm_V	Δm_K
Black body; T = 10 000 K	-0.74	0.14	0.51	1.5	0.48	0.15	0.0015
Hot plasma (Kunkel 1970b); T = 25 000, $\tau_{H\alpha} \simeq 50$	-0.70	-0.66		1.5	0.49	0.076	
Hot plasma; T = 25 000 K $\tau_{H\alpha} \simeq 75$, plus 100 K heating of 10% of photosphere	-0.68	-0.24	2.73	1.52	0.52	0.11	0.01
Hot plasma (Kodaira 1977); exactly flat energy-spectrum	-0.88	0.12	2.05	1.5	0.44	0.13	0.006
Hot plasma (Brussard & van de Hulst 1962); exact calculation for T = 1.58 × 10^5 K	-0.83	0.18	2.45	1.5	0.45	0.14	0.008
Optically thin synchrotron emission; N(E) = E$^{-2.8}$	-0.7	0.34	3.63	1.5	0.49	0.18	0.027
Inverse Compton scattering from electrons with a power-law energy spectrum (slope = -5, E_{min} = 500 keV)	-0.73	-0.06		1.5	0.48	0.13	-0.017

flare emission with $U_f-B_f=-0.7$, although it is accompanied by significantly lower emission at longer wavelengths than is usually observed. To correct for this, Kunkel proposed the addition of a much cooler second component of emission. In Table 3 we give examples of flare emission for (a) hydrogen recombination alone with $\tau_{H\alpha}=50$ and $T=25\,000\,K$, and (b) hydrogen recombination with $\tau_{H\alpha}=75$ and $T=25\,000\,K$, with the addition of blackbody radiation from an area equivalent to 10 per cent of the stellar disc at a temperature of 3100 K. This is 100 K above the temperature of the quiescent emission of AT Mic. The infrared emission in (a) is negligible and hence the infrared emission shown for (b) is that from the low-temperature component alone.

3.5 HOT PLASMA (10^5 K)

A similar hot plasma model has been proposed by Kodaira (1977) to explain observations of flare spectra (Kodaira, Ichimura & Nishimura 1976) which show negligible Balmer jumps and essentially flat energy-spectra. The small Balmer jumps imply much higher temperatures than assumed in Kunkel's (1970b) model. These higher temperatures ($\sim 10^5$ K) then account naturally for the flat energy-spectrum. Kodaira's (1977) model includes both free–free and free–bound emission, but to estimate the importance of any infrared emission we examine approximate expressions for the free–free emission alone. For optically thin free–free emission the frequency dependence of the intensity given by Lang (1974) is

$$I(\nu) \propto \ln\left(5\times 10^7\,\frac{T^{3/2}}{\nu}\right)\exp\left(\frac{-h\nu}{kT}\right),\tag{1}$$

where the logarithmic factor is an approximation to the Gaunt factor if $\nu < 5\times 10^7\,T^{3/2}$. For $\nu < kT/h$ the intensity is relatively constant (it increases only slowly towards lower frequencies). For $\nu > kT/h$ the emission falls off very rapidly. The requirement for the emission to be optically thin is met if $\nu > \nu_1$, where (Lang 1974)

$$\nu_1 = 0.53\,T^{-0.675}NL^{1/2},\tag{2}$$

N is the density and L the thickness of the source region. For frequencies less than ν_1 the source is optically thick and the emission falls off as ν^2. Thus, using the parameters of Kodaira's (1977) model ($T=10^5$ K, $N=5\times 10^{13}\,cm^{-3}$, $L=3\times 10^8$ cm), we see that the energy spectrum is relatively flat in the range $\nu_1 < \nu < kT/h$ or $15\,500\,\text{Å} > \lambda > 1400\,\text{Å}$ and falls off steeply outside this range. The short-wavelength limit is set by the temperature, but the long-wavelength limit depends also on the density and thickness of the source. Thus, although the chosen parameters imply emission to a wavelength between the J and K bands in the infrared, this is not the case for other selections of parameters. To illustrate the predictions of this model, Table 3 shows flare parameters for (a) an exactly flat energy-spectrum, and (b) a spectrum calculated by Brussard & van de Hulst (1962) which includes both free–free and free–bound emission and exact Gaunt factors for $T=1.58\times 10^5$ K.

In addition to these thermal models, several non-thermal emission processes that might account for flare radiation have been proposed. These include synchrotron emission and inverse Compton scattering, which are discussed below.

3.6 OPTICAL SYNCHROTRON EMISSION

The intensity of optically thin synchrotron emission from an isotropic distribution of electrons with a power-law energy distribution is

$$I(\nu) \simeq 0.9\times 10^{-23}\,N_0 LB^{(\alpha+1)/2}\left(\frac{6.26\times 10^{18}}{\nu}\right)^{(\alpha-1)/2}\text{erg s}^{-1}\,\text{cm}^{-2}\,\text{Hz}^{-1}\,\text{rad}^{-2},\tag{3}$$

4

where L is the thickness of the source, B is the line-of-sight magnetic field strength, and the electron energy distribution for $E>E_0$ is

$$N(E)\,dE = N_0 E^{-\alpha}\,dE. \qquad (4)$$

The frequency spectrum of the optical emission is therefore proportional to $v^{(1-\alpha)/2}$ and for $\alpha>1$ increases towards low frequencies. to produce emission with $U_f - B_f = -0.7$ requires $\alpha=2.8$. Electron energy spectra as hard as this are observed in the largest solar microwave and hard X-ray bursts and in other astrophysical plasmas, such as those found in quasars (Matthews & Sandage 1963).

If the optical spectrum is to remain a power law at frequencies at least up to U band then the energy spectrum must extend to energies given by

$$E_{max}^2\,(keV) > \frac{v_u}{16.05\,B} \qquad (5)$$

(Matthews & Sandage 1963). For example, if $v_u \simeq 0.8\times10^{15}\,Hz$ and $B=100\,G$, then $E_{max}>0.7\,GeV$. Substituting $\alpha=2.8$ into (3) and (4), we can calculate the size of a spherical, optically thin synchrotron source that would produce a flare of $\Delta m_u=1.5$ on AT Mic. If β is the ratio of the diameter of the spherical source to the stellar diameter, then

$$\beta^3 \simeq \frac{3.2\times10^{17}}{N\,B^{1.9}\,E_0^{1.8}}, \qquad (6)$$

where N is the density of synchrotron electrons with energies $>E_0\,(keV)$. A lower limit to the source size can be deduced by choosing relatively large values for the parameters in the denominator of (6) – e.g. $N=10^{10}\,cm^{-3}$, $B=1000\,G$ and $E_0=500\,keV$. The required spherical source then has a diameter about one-tenth that of the star and the total energy of the synchrotron electrons is $\sim7\times10^{32}\,erg$.

Using expressions for the absorption coefficient given by Lang (1974) we can verify that this source is indeed optically thin at optical wavelengths. In fact, at its centre the source becomes optically thick ($\tau=1$) at $v\simeq2.9\times10^{12}\,Hz$ and at $v=5\,GHz$, $\tau\simeq10^9$. The ratio of optical to microwave luminosity (as defined in Section 3.8) is $\sim10^9$ for this particular model. For choices of parameters that require larger source sizes, this ratio is reduced and is approximately unity in the extreme case where the source remains optically thin down to microwave frequencies.

Flare parameters for this model are shown in Table 3. It predicts somewhat excessive emission in the red and infrared. This can of course be modified by varying the slope of the electron energy spectrum. An exactly flat energy-spectrum with $U_f - B_f = -0.88$ can only be produced if the electron energy spectrum is impossibly hard ($\alpha=1$).

3.7 INVERSE COMPTON SCATTERING

The inverse Compton scattering model of flare star emission was proposed by Gurzadyan (1980). It is a non-thermal model in which infrared photons scatter off mildly relativistic electrons to produce higher-energy photons in the visible or ultraviolet. Thus, because infrared photons are scattered to higher energies, the optical flare is expected to be accompanied by a decrease in infrared emission.

Gurzadyan's (1980) model assumes mono-energetic electrons with Lorentz factor γ, but since a source for mono-energetic electrons has not yet been established, we consider here the scattering of the photospheric emission $B(v)$ from an overlying layer of electrons with a power-law energy distribution given by $N(\gamma)=K\gamma^{-\alpha}$. Such distributions are relatively common in astrophysical

situations. We are then also in a position to examine the gyrosynchrotron emission at microwave frequencies from electrons with similar energy distributions.

The energy of the scattering electrons far exceeds that of the photons. As a result a scattered photon moves nearly in the direction of the scattering electron. If the latter are assumed isotropic in direction then the photons are scattered into 4π sr. Following a procedure similar to that used by Gurzadyan for monoenergetic electrons, we find that the intensity of the emission emerging after scattering from a power-law distribution of electrons is

$$I(\nu)=B(\nu)\left[1+\frac{\alpha-3}{8\pi}\tau\{\exp(X)-1\}X^{-(\alpha-1)/2}\int_0^X\frac{U^{(\alpha-1)/2}}{\exp(U)-1}dU\right]\exp(-\tau),\qquad(7)$$

where $X=H\nu/kT$, $U=h\nu_0/kT$ (ν_0 varies from 0 to ν in the integral) and

$$\tau=\frac{\alpha-1}{\alpha-3}\sigma_T\gamma_{\min}^2N_c.\qquad(8)$$

$B(\nu)$ and T are the intensity and effective temperature of the non-flaring photospheric emission, σ_T is the cross-section for Thomson scattering and N_c is the columnar density of electrons with energies greater than $\gamma_{\min}$.

In the special case where the layer of electrons has a cross-sectional area equal to the area of the stellar disc, $I(\nu)$ describes the emission from the whole star during the flare and $2.5\log I(\nu)/B(\nu)$ is the magnitude of the flare at frequency ν. For our usual model flare with $\Delta m_U=1.5$ and $U_f-B_f=-0.7$, we find that $\tau=0.017$ and $\alpha=5$. The required columnar density of electrons with energies above 500 keV ($\gamma_{\min}=2$) is 3.3×10^{21} cm^{-2}. For reasonable volume densities, the scattering layer must therefore be many stellar radii thick and the total energy of the electrons ($\sim6\times10^{36}$ erg) equals the photospheric energy output for many days.

Flare parameters for this model are included in Table 3. Compared to the other models this one is, of course, distinguished by predicting a 'negative' flare in the infrared. The number of energetic electrons required and their total energy are four orders of magnitude greater in this model than in the synchrotron model. On the other hand, the inverse Compton model requires only a relatively soft electron-energy spectrum.

3.8 MICROWAVE EMISSION

Although observations at 5 GHz were in progress during 10 optical flares, only one flare was accompanied by significant ($>3\sigma$) microwave emission (Fig. 4). On the other hand, two microwave bursts were observed with no optical counterparts. A fourth burst was detected while U-band observations were obscured by cloud. A further four flares were possibly accompanied by microwave bursts. In these cases, individual 2-min integrations of the microwave emission were less than 3σ but longer integrations were more significant. Included in this category are the two smaller flares in Fig. 4. An earlier simultaneous microwave and optical flare at 1057 UT on 1980 October 25 on AT Mic was reported by Slee *et al.* (1981). Data from that event will also be included in this discussion.

It may be fortuitous, but it is worth noting that the two microwave bursts that are definitely associated with optical flares are 'extended' in nature (e.g. Fig. 4 and figure 1 of Slee *et al.* 1981), whereas the two microwave bursts that are not associated with optical flares are 'impulsive' and persist for only about one 2-min integration period.

Fig. 5 shows the relationship between the peak flare intensities at 5 GHz and in B. In this instance we depart from our normal procedure of categorizing flares by their U mag. This is because the two flares detected both at optical and microwave wavelengths were only observed
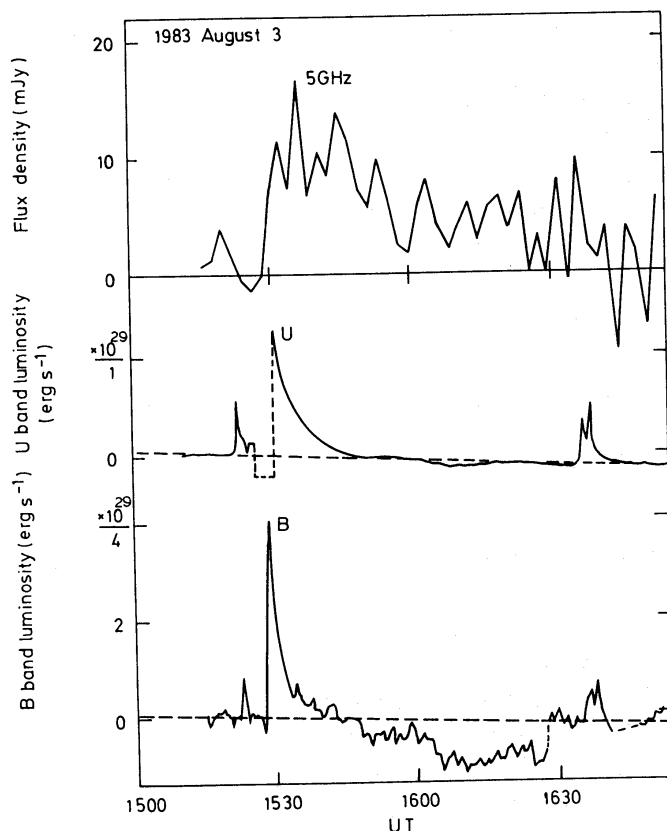
G. J. Nelson et al.

Figure 4. Simultaneous observations of flares on AT Mic at 5 GHz and in U and B. Calibration observations were in progress in U at the start of the largest flare. Note the impulsive nature of the optical flare compared to the extended burst at 5 GHz. The baseline for the microwave burst was determined from observations made at the same hour angle in the absence of a flare. This removes the effects of confusing sources in the sidelobes of the antenna (Slee *et al.* 1981).
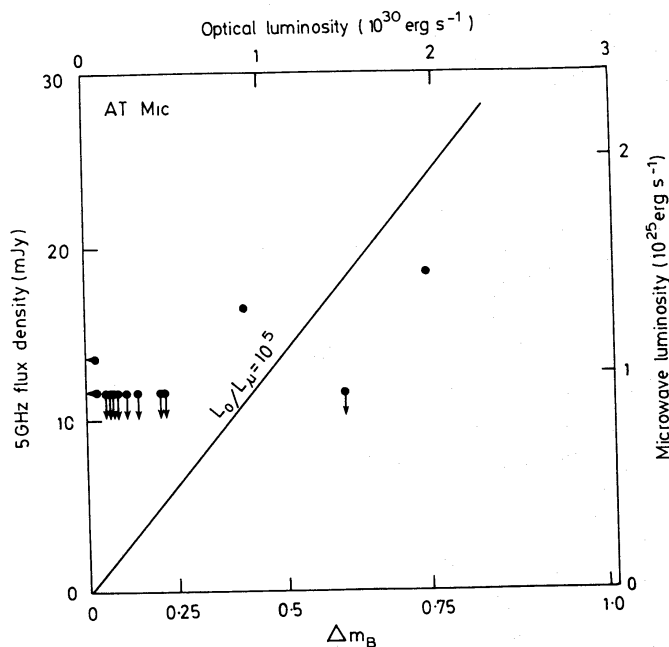

Figure 5. The energy flux at 5 GHz and in B for 13 flares on AT Mic. The majority of flares were not detected at 5 GHz and hence only upper limits are indicated. Observations in U have been corrected to B assuming $U-B=-0.7$. The luminosity scales have been assigned assuming radiation into 4π sr and bandwidths of 10 GHz and 3000 Å (from 4000 to 7000 Å) at microwave and optical wavelengths respectively. For the two events detectable at both optical and microwave wavelengths the average ratio L_0/L_μ at flare maximum was $\sim10^5$. This ratio is indicated by the line on the figure.

completely in *B*. In other events where only *U* intensities are available they have been converted to *B* using the relation $U-B=-0.7$. Also shown on Fig. 5 are estimates of the optical and microwave flare luminosities. The microwave luminosity assumes an effective emission bandwidth of 10 GHz, which is typical for large solar microwave bursts. The optical luminosity is calculated assuming a flat energy-spectrum in the range 4000–7000 Å. Both luminosities assume emission into 4π sr.

For the two events in which significant 5 GHz and *B* emission were detected, the average ratio of optical to microwave luminosities $L_0/L_\mu \simeq 10^5$. However, it is clear from the events where significant emission was detected either only in *B* or at 5 GHz that, at flare maximum, L_0/L_μ may at times be $<5\times10^3$ or $>1.6\times10^5$. It is also clear for the event illustrated in Fig. 4 that the optical and microwave bursts begin simultaneously (within the limits of the observing time constants) but the optical emission decreases more rapidly with time. Consequently L_0/L_μ decreases to very small values late in the flare. This was also the case for the large microwave burst on AT Mic reported by Slee *et al.* (1981) and is also true for many large solar bursts. Energetic electrons accelerated or trapped high in the solar corona continue to radiate at microwave frequencies well after the thermal electrons responsible for the optical flare have cooled. A similar scenario probably applies in the case of stellar flares and certainly accounts for the wide variation in L_0/L_μ observed between flares at flare maximum (Fig. 5) and throughout the duration of individual flares (Fig. 4).

The average values of L_0/L_μ at flare maximum reported here for AT Mic are in agreement with values reported by Slee *et al.* (1984) for Prox Cen and AU Mic. They are also of the same order as deduced by Lovell (1969) and Kunkel (1969) for L_0/L_m, where L_m is the luminosity at metre wavelengths. The total rates of energy release in microwave and metrewave bursts are therefore probably comparable. The metrewave emission is nevertheless much more intense, since the energy is released into a narrower bandwidth and in addition may continue for a longer time (Nelson *et al.* 1979). This situation is parallel to the solar case, where quite different emission mechanisms are involved in the two wavelength-ranges. The majority of solar metrewave bursts probably result from the conversion of Langmuir waves, whereas the majority of microwave bursts probably involve gyrosynchrotron emission from mildly relativistic electrons. For these solar bursts, brightness temperatures as high as 10^{15} K have been observed for Langmuir-wave conversion compared to only about 10^{10} K for gyrosynchrotron emission. For the AT Mic flare at 1530 UT on 1983 August 3 the brightness temperature at 5 GHz is 7×10^9 K, assuming a source the size of the star. Under the same assumption the 240-MHz flare on YZ CMi reported by Lovell (1969) had a brightness temperature of 10^{15} K. There is evidence that thermal ($\sim10^8$ K) sources about the size of the star are required to account for the soft X-ray emission observed during stellar flares (Kodaira 1977; Kahn *et al.* 1979). The non-thermal stellar radio sources may therefore be of similar size. If they are in fact much smaller, then the actual brightness temperatures would be orders of magnitude greater than those detected on the Sun.

Such high brightness temperatures would certainly require coherent emission mechanisms. It is of interest, however, to calculate the number of mildly relativistic electrons that would be required to produce, by incoherent gyrosynchrotron emission, the microwave emission observed at 1530 UT on 1983 August 3 (Fig. 4). This number will be greater than required with a coherent mechanism and will thus set an upper limit to the number of electrons that might be available for inverse Compton scattering. Using the equations given by Dulk & March (1982) for optically thick gyrosynchrotron emission from electrons with a power-law energy distribution, we have

$$N_c > 8\times10^{23} B^{-5.2}. \qquad (9)$$

N_c is the columnar density of electrons with energies above 500 keV, the assumed distribution has a slope of -5 and the viewing angle to the magnetic field is 45°. Thus N_c can vary enormously

depending on the magnetic field in the source. For $B=10\,G$, $N_c>5.0\times10^{18}\,cm^{-2}$, and for $B=100\,G$, $N_c>3.2\times10^{13}\,cm^{-2}$. The brightness temperature of the source also depends on B, but for $B=10\,G$ it is $\sim7\times10^9\,K$, which is consistent with a source about the size of the star for the burst on 1983 August 3.

We are now in a position to see whether the electrons needed to produce this microwave burst by gyrosynchrotron emission are sufficient in number to produce the accompanying optical flare by inverse Compton scattering. We consider here scattering from a similar distribution of electrons to that above (i.e. a power-law energy spectrum of slope -5). The optical emission was slightly less in this event than in the one considered in Section 3.2. The required columnar density of electrons with energies greater than 500 keV is $\sim2.7\times10^{21}\,cm^{-2}$. If these electrons are contained in a magnetic field, the condition that the magnetic energy density exceed the electron energy density requires

$$B>5.2\times10^{-3}N^{1/2}. \tag{10}$$

Limits can be placed on the value of N because, if it is too large, the 5-GHz radiation cannot propagate; on the other hand, if it is too small the source has to be too deep. A compromise value is $N=10^{10}\,cm^{-3}$, for which the source is 12 stellar radii deep, the plasma frequency is $\sim1\,GHz$ and the required magnetic field strength is $>500\,G$. However, in a field as large as this, only $6\times10^9\,cm^{-2}$ electrons are required to produce the observed microwave emission (equation 9). Thus a number of electrons greater by >11 orders of magnitude are required to produce the observed optical emission by inverse Compton scattering than to produce the microwave emission as gyrosynchrotron radiation. In this situation the microwave emission would clearly be optically thick and would come from the very edges of the inverse Compton scattering region. The brightness temperature would be 10^9 to $10^{10}\,K$, depending on the actual energy distribution of the electrons. The flux would depend on the cross-sectional area of the region and, contrary to observation, virtually all optical flares would produce detectable microwave emission.

Conversely, of course, if the number of energetic electrons present is just sufficient to make the microwave source optically thick, then the associated optical emission due to inverse Compton scattering would not be detectable.

3.9 843-MHz OBSERVATIONS

The first radio detections of flare stars were made at metre wavelengths and were particularly significant because of the very high brightness temperatures inferred from them. More recently, detections of flares at microwave frequencies have been made. As discussed in the previous section, emissions in the two frequency-ranges are probably due to different mechanisms. At intermediate frequencies the spectra of both of these emissions are likely to decrease but, if the solar example is any guide, a rich variety of additional types of burst may occur (Wiehl, Benz & Aschwanden 1985). In particular, an additional emission mechanism, electron cyclotron maser emission (Melrose & Dulk 1982), might be expected to occur as well. It is characterized by very high brightness temperatures (up to $10^{17}\,K$), rapid flux variations and high circular polarization.

The 843-MHz observations reported here were made in an attempt to detect emissions of this type but there were no unambiguous detections, either with the fan beam and a 96 s time constant or with the synthesized pencil beam and an integration time of 12 hr. These place upper limits of 100 to 200 mJy on impulsive flare emissions and $\sim3\,mJy$ for quiescent or very long duration flare events. The corresponding brightness temperature limits are $5\times10^{12}/\beta^2\,K$ and $10^{11}/\beta^2\,K$, where β is the ratio of the source size to the size of the star.

3.10 INFRARED OBSERVATIONS

Only one optical flare was accompanied by a significant change in infrared flux. The flare was observed by the Anglo-Australian Telescope at 163240 UT on 1982 July 10 as a 0.48-mag increase in B with a simultaneous *increase* of 0.005 ± 0.001 mag in K (Fig. 6). This result needs to be corroborated because it has important implications for the theory of flare star emission. Although none of the other individual flares appears to have infrared counterparts, it is possible that by averaging the observations for a large number of smaller flares a significant average result might be obtained.

On 1983 August 1, 2 and 3 a total of 14 flares were observed in both U and J at Mt Stromlo. Summing the peak intensity in U for each of these flares yields a mean U magnitude of 0.80 ± 0.015. For comparison, the J intensity during each flare has been calculated by taking a 10 s average at the time of the peak and subtracting a background found by averaging for 2 min before the start of the flare. The mean J intensity calculated in this way was 0.0007 ± 0.0006 mag. Although the significance of this result cannot be deduced directly from Table 3, for an exactly flat energy-spectrum a J band magnitude of 0.002 would have been expected, and for the inverse Compton scattering model of section 4.2 a negative flare of -0.006 mag would have been expected. either of these predicted averages could have been detected to our 3σ level of 0.0018 mag but was not.

It is of interest now to compare these observational results in some detail with the predictions of the various models summarized in Table 3. Apart from the 10 000 K blackbody and the 25 000 K hot plasma model (Kunkel 1970b), all models predict detectable flares in the infrared. The blackbody model can be rejected because of the enormous energy input required to heat a portion of the photosphere to 10 000 K. This is particularly difficult if the energy source is in the corona. In any case such heating would probably not be uniform, and cooler parts of the flare could contribute to a detectable infrared flux. Likewise the 25 000 K hot plasma model can be rejected because it predicts too large a value for B_f-V_f. When a small 'white light' or photospheric heating component is added to the model to correct this deficiency then a relatively large infrared component is also predicted.
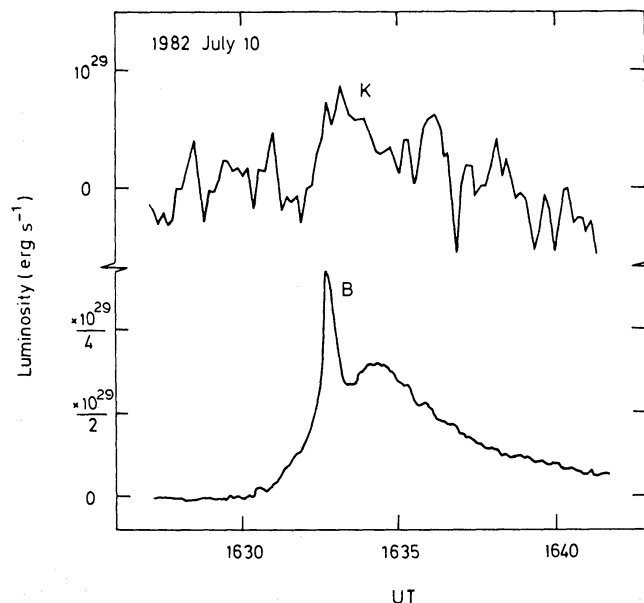

Figure 6. Simultaneous Anglo-Australian telescope observations of a large flare on AT Mic in the visible (B) and infrared (K). At the peak of the flare $\Delta m_B = 0.48$ and $\Delta m_K = 0.005$.

Both of the non-thermal models discussed can probably be rejected because they involve implausibly large numbers of energetic electrons and total energies. The synchrotron model can account for the present optical and microwave observations, including values of L_0/L_μ that vary from flare to flare and with time. It produces far too much infrared emission, however, which can only be reduced by assuming impossibly hard electron-energy spectra. The inverse Compton scattering model is certainly not the dominant mechanism, because 'negative' infrared flares are not observed. It is possible, although unlikely, that the absence in most cases of detectable infrared flares results from a combination of a 'negative' flare produced by the inverse Compton scattering mechanism and a 'positive' flare produced by one of the other mechanisms represented in Table 3.

More directly, one can account for the usual absence, but occasional occurrence, of positive infrared flares with the hot plasma model of Kodaira (1977) (Table 3). As discussed in Section 4.2, the wavelength range, for which emission in this model is significant, depends on parameters of the flare. In the simplified case of free–free emission alone, the short-wavelength limit is determined solely by the temperature ($v_2 = kT/h$) but the long-wavelength limit depends as well on the density and depth of the source region ($v_1 = 0.53\,T^{-0.675}NL^{0.5}$).

For temperatures much below 10^5 K, v_1 may exceed v_2 and no region of flat energy-spectrum will occur. This is essentially Kunkel's (1970b) model (Table 3). The fact that the observed spectrum is generally flat in the U, B and V bands and apparently seldom extends as far as the J and K bands in the infrared imposes quite severe restrictions on N, T and L in the source. For example, Fig. 7 shows values of N and L for $T = 10^5$ K and for low-frequency cut-offs at 5.45, 2.40 and 1.36×10^{14} Hz, corresponding to V, J and K bands respectively. For most flares, N, and L must lie between the V and J band lines, but for flares with infrared components they may extend to lower values. The lines in Fig. 7 move up or down slightly if the temperature is above or below 10^5 K.

Within the wavelength range for which the energy spectrum is relatively flat the intensity given by Lang (1974) is

$$I \propto N^2 LT^{-0.5}A \quad \text{or} \quad I \propto v_1^2 T^{0.85}A, \tag{11}$$

where A is the area of the flare region. Thus flares with spectra extending into the infrared (i.e.
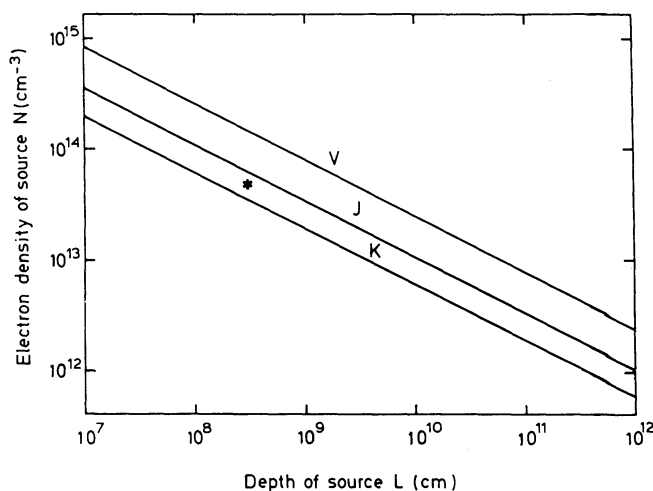

Figure 7. Values of electron density and source depth for which the long-wavelengths cut-off for free–free bremsstrahlung occurs at the centre of the V, J and K bands respectively. At wavelengths between this cut-off and $\lambda = hc/kT$ the energy spectrum is relatively flat. A plasma temperature of 10^5 K is assumed. The asterisk represents the parameters used in Kodaira's (1977) model.

flares with low values of N or L) will be significantly weaker than their counterparts with higher-frequency cut-offs.

It is possible then that flares with a wider range of values of N and L than suggested in Fig. 7 actually occur, but the observations are weighted towards those which do not extend into the infrared. An alternative explanation is that N and L are relatively constant parameters determined by the properties of the stellar chromosphere. In this case the variations in intensity between flares reflect mainly changes in area, and only small variations in the low-frequency flare spectra would be expected. The flare spectrum might then vary more from star to star than from flare to flare on the same star. Stars with shallower or less dense chromospheres (and hence with weaker flares) would be more likely to produce infrared flares. Indeed Haro & Chavira (1966) report the existence of two extreme types of flare star in the Orion nebula. In one, the flare continuum emission, while strong in U and B, barely extends to visible wavelengths but the emission lines are strong. In the other type, the continuum extends well into the red and emission lines are almost absent. These observations suggest large values of N and L in the flare plasma on the first type of star and small values on the other.

4 Conclusions

The sensitivity of the infrared observations reported here is such that *decreases* in the infrared flux at the time of individual large flares, or averaged over a large number of smaller flares, would have been detected if inverse Compton scattering were the dominant flare process. The fact that microwave bursts are detected during stellar flares implies the existence of electrons with sufficient energies to scatter infrared photons into the visible and ultraviolet. The absence of 'negative' infrared flares indicates, however, that this is not the mechanism responsible for most of the optical flare emission. This is further confirmed by the observation of great variability in the ratio of optical to microwave luminosities. If the same population of mildly relativistic electrons were responsible for optical emission by inverse Compton scattering and for microwave emission by gyrosynchrotron emission, a much closer relationship might be expected. Indeed *all* optical flares produced by inverse Compton scattering would be accompanied by detectable microwave bursts. This is because the numbers of scattering electrons required and the magnetic field strength that must be present to contain them far exceed the requirements for the emission of detectable gyrosynchrotron radiation.

The majority of the infrared observations revealed no detectable change during flares, but one large optical flare was accompanied by a significant *increase* in infrared flux. These observations, taken together with the value of $U_f - B_f = -0.7$ observed during flares, lend strong support for the hot ($\sim 10^5$ K) plasma model of Kodaira (1977).

If this model is the mechanism responsible for optical emission during stellar flares then observations of the flare spectrum to wavelengths both longer and shorter than the visible will be important. They will serve not only to validate the model further but will in turn yield important source parameters. In particular the long-wavelength limit will reveal the depth and density of the source region which may vary significantly between stars. In principle, the short-wavelength limit should define the temperature of the source. This limit may, however, be confused by EUV emission from the less dense but hotter (10^8 K) and much more extensive plasma which gives rise to the soft X-ray emission during flares. Yet a third even hotter plasma or population of non-thermal electrons must exist to account for the microwave emission observed during some flares. The mechanism for heating or accelerating these electrons may be related only indirectly to the main flare processes.

Acknowledgments

References

Allen, C. W., 1973. *Astrophysical Quantities*, Athlone Press, University of London.

Brussard, P. J. & van de Hulst, H. C., 1962. *Rev. Mod. Phys.*, **34**, 507.

Dulk, G. A. & Marsh, K. A., 1982. *Astrophys. J.*, **259**, 350.

Fisher, P. L. & Gibson, D. M., 1982. In: *Proc. Second Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, eds Giampapa, M. S. & Golub, L., Vol. II, p. 109, SAO, Cambridge.

Grindlay, J. E., 1970. *Astrophys. J.*, **162**, 187.

Gurzadyan, G. A., 1980. *Flare Stars*, Pergamon Press, Oxford.

Haro, G. &. Chavira, E., 1966. In: *Vistas in Astronomy*, Vol. 8 Proc. Conf. held in Flagstaff, Arizona, June 1964, p. 89, Pergamon Press, Oxford.

Joy, A. H. & Abt, H. A., 1974. *Astrophys. J. Suppl. Ser.*, **28**, 1.

Kahn, S. M., Linsky, J. L., Mason, K. O., Harsch, B. M., Bowyer, C. S., White, N. E. & Pravdo, S. H., 1979. *Astrophys. J.*, **234**, L107.

Kodaira, K., 1977. *Astr. Astrophys.*, **61**, 625.

Kodaira, K., Ichimura, K. & Nishimura, S., 1976. *Publs astr. Soc. Japan*, **28**, 665.

Kunkel, W. E., 1969. *Nature*, **222**, 1129.

Kunkel, W. E., 1970a. *IAU Information Bulletin on Variable Stars, No. 442, IAU Commission 27*, Konkoly Observatory, Budapest.

Kunkel, W. E., 1970b. *Astrophys. J.*, **161**, 503.

Kunkel, W. E., 1973. *Astrophys. J. Suppl. Ser.*, **25**, 1.

Lang, K. R., 1974. *Astrophysical Formulae*, Springer-Verlag, New York.

Lovell, B., 1969. *Nature*, **222**, 1126.

Matthews, T. A. & Sandage, A. R., 1963. *Astrophys. J.*, **138**, 30.

Melrose, D. B. & Dulk, G. A., 1982. *Astrophys. J.*, **259**, 844.

Nelson, G. J., Robinson, R. D., Slee, O. B., Fielding, G., Page, A. A. & Walker, W. S. G., 1979. *Mon. Not. R. astr. Soc.*, **187**, 405.

Pettersen, B. R., 1976. *Inst. Theor. Astrophys., Oslo, Rep. No. 46*, Universitetsfor lagets trykningssentral, Oslo.

Slee, O. B., Tuohy, I. R., Nelson, G. J. & Rennie, C. J., 1981. *Nature*, **292**, 220.

Slee, O. B., Allen, W. H., Coates, D. W., Page, A. A., Quinn, P. J. & Tuohy, I. R., 1984. In: *Proc. IAU Second Asian-Pacific Regional Meeting in Astronomy*, held Bandung, Indonesia, August 1981, Reidel, Dordrecht, Holland.

Wiehl, H. J., Benz, A. O. & Aschwanden, M. J., 1985. *Solar Phys.* **95**, 167.