N95- 14508

20097
p. 8

OBSERVATIONS OF HOT STARS AND ECLIPSING BINARIES WITH FRESIP

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ABSTRACT

The FRESIP project offers an unprecedented opportunity to study pulsations in hot stars (which vary on time scales of a day) over a several year period. The photometric data will determine what frequencies are present, how or if the amplitudes change with time, and whether there is connection between pulsation and mass loss episodes. It would initiate a new field of asteroseismology studies of hot star interiors. A search should be made for selected hot stars for inclusion in the list of project targets. Many of the primary solar mass targets will be eclipsing binaries, and I present estimates of their frequency and typical light curves. The photometric data combined with follow up spectroscopy and interferometric observations will provide fundamental data on these stars. The data will provide definitive information on the mass ratio distribution of solar-mass binaries (including the incidence of brown dwarf companions) and on the incidence of planets in binary systems.

1. Hot Star Variability

There is growing evidence that many O- and B-type stars are nonradial pulsators (NRP) with periods on the order of a day (Baade 1987; Fullerton 1991; Cuypers 1991; Walker 1991). This time scale is problematical for ground-based observers, and we have only a preliminary notion of the pulsation characteristics of massive stars. Continous photometric monitoring of these stars over several years would lead to a vast improvement in our understanding. Many objects are known to be multi-periodic (Smith 1985; Gies & Kullavanijaya 1988; Waelkens 1991), and I suspect that most will turn out to be multi-periodic. However, to approach the kind of results found for white dwarf pulsations, where observers can obtain continuous data over 1000 cycles (cf. Winget et al. 1992), would require 2 years of continous monitoring for a Be star pulsator like λ Eri (Balona et al. 1992). The great attraction of studying NRP in hot stars is that in most cases the stars are rapid rotators, and consequently the rotational Doppler line broadening reflects the longitudinal distribution of the pulsations across the visible hemisphere. Thus combined spectroscopic and photometric studies can lead to the detection of relatively high-order pulsations.

There are many potential scientific gains from continuous monitoring. The following are some representative cases involving time scales on the order of a day:

Be stars: Most Be stars display line profile variability consistent with low order NRP (Baade 1987), and the same periods are found in the photometry ($\Delta m \approx 0.05$ mag; Percy 1987). Both the photometric amplitude and Be emission activity vary on time scales of months to years. Since NRP is a potential source of energy to promote mass loss into a circumstellar disk, it is important to search for a correlation between pulsation activity and Be emission episodes.

O stars: A few O stars are known multi-periodic line profile variables (cf. ζ Oph, Reid et al. 1993). The stars are also photometric variables but the variations are complex (termed "microvariability"; cf. Balona 1992).

Slowly pulsating B stars: A growing number of B stars are found to be multi-periodic, photometric variables (cf. 53 Per, Buta & Smith 1979; Waelkens 1991). Beating between the signal frequencies can only be sorted out over very extended time scales (often longer than a typical observing season).

The long periods indicate the presence of g-mode pulsations which should represent an important probe of hot star interiors. Saio & Lee (1991 and references therein) show that NRP in Be stars could result from coupling with convective motions in the core; thus the phase motion of NRP in the photosphere reflects the core rotation rate. Data accumulated over several years would provide the means to begin significant asteroseismology studies of hot star interiors.

2. Hot Star Content in the Selected Region

Are there interesting hot star targets in the regions near $(l, b) = (90°, +15°)$ or $(l, b) = (89°, +11°)$? Unfortunately, the massive star population dwindles rapidly at high Galactic latitudes, so the sample will be limited. There are no O stars with $V < 9.0$ in these regions (Cruz-González et al. 1974). Since $V = 9.0$ corresponds to a height of $z = 1$ kpc for an O8 V star at $b = +15°$, and since the the scale height for O stars is 73 pc, there will be few if any O stars found in the proposed fields of view (FOV). There is one B5 V star, HD 188665 (HR 7608 = 23 Cyg), near the center of the $b = 15°$ FOV. The *Bright Star Catalogue* (Hoffleit 1982) lists the star as a possible velocity variable, so this may be a pulsator. There are several known B stars in the $b = 11°$ FOV (HD 195554, HD 196421, and the Be star HD 194883). However, all these stars are bright ($V < 8$), so a neutral density filter would be required.

I expect that there are many fainter B stars that remain undetected in these fields. The number of B stars, N, fainter than some limiting V_b can be estimated from

$$N = \Delta\omega\ \rho_\circ\ \alpha^{-3}\ e^{-\alpha r}\Big((\alpha r)^2 + 2\alpha r + 2\Big),$$

where $\Delta\omega$ is the angular area of the field, the local space density of B stars is $\rho_\circ = 1 \times 10^{-4}$ pc^{-3} (Mihalas & Binney 1981), α is the ratio of $\sin b$ to the scale height $\beta = 69$ pc (Abt 1987), and r is the distance corresponding to V_b. The extinction is $A_V = 0.64$ (1.66) mag in the $b = 15°$ (11°)

FOV (Burstein & Heiles 1982); thus, for $V_b = 10$, the distance of a B3 V star (with $M_V = -2.0$) is $r = 1870$ (1170) pc. Therefore, the number of B stars in the FOV fainter than $V = 10$ is ≈ 37 (92); $\approx 18\%$ of these will be type Be (Abt & Cardona 1984). Thus even after deletion of the bright stars (and the need for neutral density filters), there will be a significant number of targets for study.

The great potential of continous monitoring with the FRESIP mission could easily be extended to this sample of B and Be stars in the FOV. Such targets should be selected by spectroscopic observations of blue objects in the FOV.

3. Eclipsing Binaries among the Main Targets

Many of the solar mass targets of the FRESIP program will be eclipsing binaries with stellar companions. The light curve data on these systems will provide fundamental data (masses and radii) when combined with spectroscopic data.

Mayor et al. (1992) report on the binary properties of a volume limited sample of G- and K-type main sequence stars (from CORAVEL radial velocity measurements of some 900 stars over a time span of > 10 years combined with visual binary and common proper motion data). They find that the period distribution has a Gaussian shape in log P (mean period of 170 y). The mass ratio distribution is approximately flat but they argue that the numbers could rise at the low mass end.

The period distribution can be transformed to a semi-major axis distribution for an assumed mass ratio. This in turn can be used to obtain a probability distribution for a stellar eclipse. This probability distribution is illustrated as a function of semi-major axis a in Figure 1. The integrated probability of finding an eclipsing system at any a is 0.4% (or 0.9% according to the binary frequency found by Abt & Willmarth 1992). This result is essentially independent of the assumed mass ratio. The lower limit for the integration, $a = 2\ R_\odot$, probably represents a contact binary (Mochnacki 1981). The mean observed semi-major axis for these eclipsing systems is 0.13 AU ($P = 14.6$ d).

I have calculated eclipse light curves (V-band) for several types of companions. These models take $P = 14.6$ d and $i = 90°$, and assume that the primary is a solar mass star with the Sun's radius. The assumed flux (Kurucz 1970) and limb darkening law (Wade & Rucinksi 1985) for the solar mass primary were taken from a $T_{\rm eff} = 5500$ K and $\log g = 4.5$ model atmosphere. The input parameters and eclipse depths (Δm_p for primary superior conjunction) are given in Table 1. The full duration of the eclipse is given by Δt.

The K star model light curve illustrated in Figure 2 was made with the synthesis program of Mochnacki & Doughty (1972). The model flux and limb darkening for $T_{\rm eff} = 4000$ K and $\log g = 4.0$ were taken from Carbon & Gingerich (1969). Both primary and secondary eclipse are easily visible.

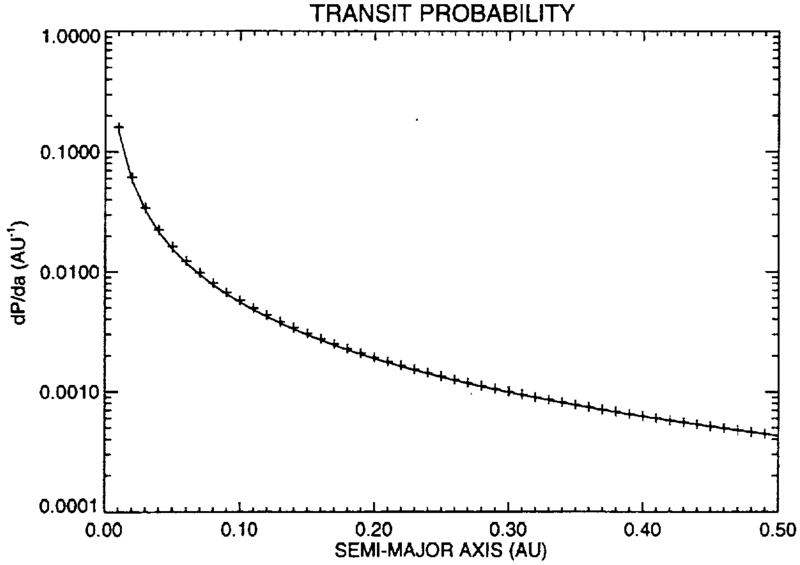

Fig. 1.— The probability of a transit of the center of a star across a solar mass dwarf as a function of a (based on the period distribution of Mayor et al. 1992). The solid line shows the distribution for a mass ratio $q = M_2/M_1 = 1$ while the plus signs show the nearly identical distribution for $q = 0$.

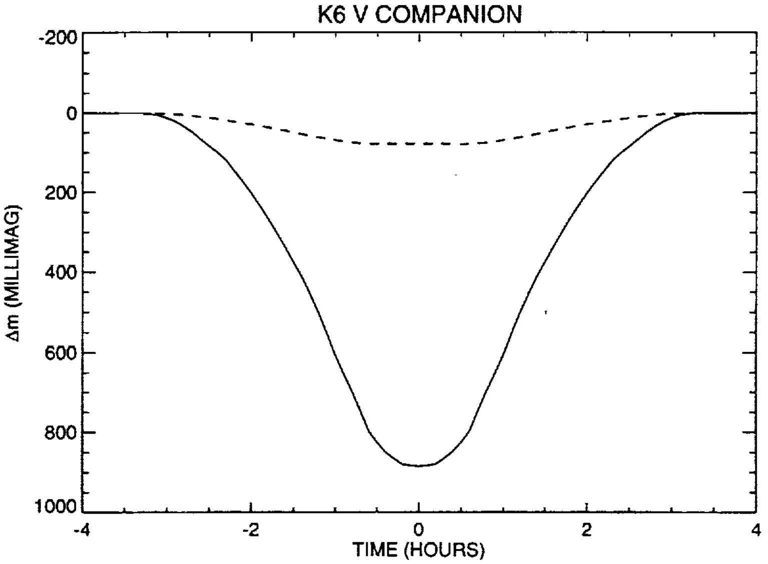

Fig. 2.— The primary (*solid*) and secondary (*dashed*) eclipses of a K-dwarf around a solar type star.

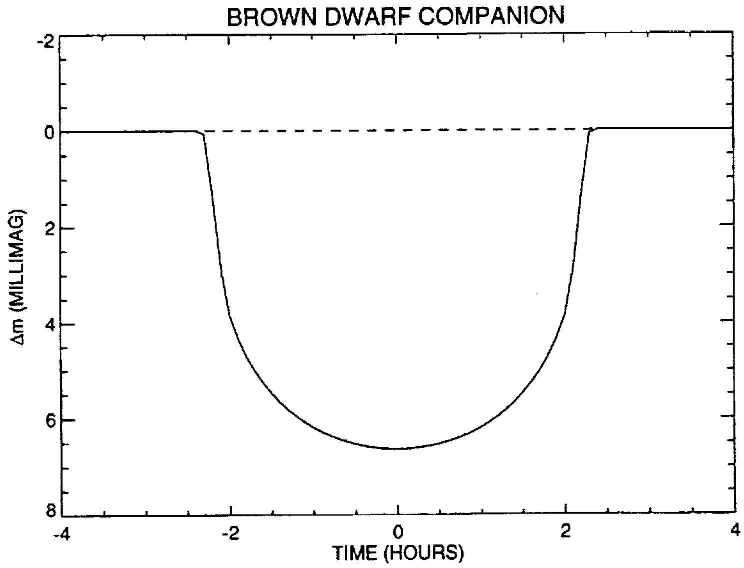

Fig. 3.— The primary (*solid*) and secondary (*dashed*) eclipses of a late M-dwarf (or brown dwarf) around a solar type star.

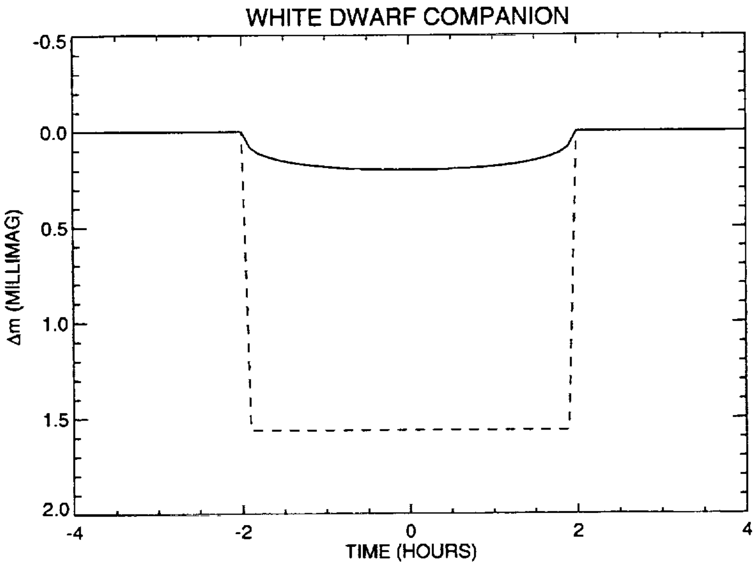

Fig. 4.— The primary (*solid*) and secondary (*dashed*) eclipses of a DA white dwarf around a solar type star.

An eclipse by a late M-dwarf or brown dwarf is shown in Figure 3. Parameters for a possible brown dwarf companion were taken from Kirkpatrick et al. (1993) for GD 165B. For this case (and the next), a simple analytical light curve was used. A star this faint acts only as an opaque disk; no secondary eclipse is seen. The variation during primary eclipse reflects the limb darkening of the solar mass primary (thus the shape of the eclipse should help determine the inclination).

Finally I calculated an eclipse for a white dwarf star (Fig. 4). Parameters for a DA white dwarf companion were taken from Bergeron et al. (1992) for $T_{\rm eff}$ = 11000 K and log g = 8.0. Because of the larger surface flux of the hotter white dwarf, the secondary eclipse (white dwarf behind) is the deeper one in this case.

The final column in Table 1 lists the amplitude of the reflex motion that would be observed in the solar mass star. Each of these cases would be detected with high resolution spectroscopy, and the combined light curve and spectroscopic data would yield the inclination and limits on the masses (masses follow if the system is double-lined or a mass estimate is made for the primary). Precise secondary radii could also be determined with a time resolution better than Δt = 1 hour.

The FRESIP data will yield a definitive mass ratio distribution for solar-mass binaries. This will be of crucial importance in determing the frequency of low mass stellar or brown dwarf companions. If any of these eclipsing binaries also host planetary systems, then it is probable that planetary transits will also be observed since the stellar and planetary orbital planes are likely to be nearly coincidental. Thus the FRESIP program will provide key data on the occurrence of planets in binary systems.

Table 1. MODEL ECLIPSE DEPTHS

Star	M ($M_\odot$)	R ($R_\odot$)	Flux Ratio (F_s/F_p)	Δt (h)	Δm_p (mmag)	Δm_s (mmag)	K_1 (km s^{-1})
K6 V	0.64	0.718	7.5×10^{-2}	6.5	885	79	40.1
GD 165B	0.08	0.069	2.6×10^{-4}	4.6	6.6	2.8×10^{-5}	6.6
DA	0.52	0.012	1.4×10^{-3}	3.9	0.20	1.56	34.2

4. Complementary High Angular Resolution Studies

Over the next decade many close binaries will be resolved with optical interferometers. The Center for High Angular Resolution Astronomy at Georgia State University (H. A. McAlister, Director) is completing plans for the CHARA Array, a 7-element optical/IR interferometer with a 400-m baseline. This telescope will resolve binaries down to separations of 0.2 milliarcsec and magnitude differences of $\Delta m = 3$ (for objects with $V < 12$). For solar-type targets of $V = 10$ at a distance of 100 pc, all binaries with $P > 0.8$ d will be resolved. Such binaries will probably be double-lined systems, and the combination of interferometric, spectroscopic, and light curve data will yield accurate inclinations, masses, radii, and distances to the systems. The CHARA Array will also be used to search for Jupiter-sized planets in wide binaries by measuring reflex motion in the residuals from the binary orbit.

This work was supported in part by NSF grant AST-9115121.

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III. EXTRAGALACTIC OBJECTS