SCANNER OBSERVATIONS OF GAMMA CASSIOPEIAE

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Abstract. The photoelectric spectrophotometric scans of γ Cas have been analysed to find the stellar and envelope parameters. The absolute energy distribution of γ Cas covering the wavelength interval λ350–700 nm have been given. Its effective temperature and gravity have been estimated by a comparison of the observed energy distribution curves with appropriate model atmospheres. The temperature has also been determined by Zanstra's method from the total energy emitted in the Hα-line. The mass, radius, luminosity, photospheric electron density and mass-ejection rate for γ Cas have been derived. An estimate of the extension of the stellar envelope has been made by use of the dilution factor obtained from the Balmer decrement. Electron density and electron temperature in the envelope are estimated.

1. Introduction

The Be star γ Cas (= HD 5394, B0.5 IV) has irregular luminosity and spectral changes and often shows transient shell spectra (Hutchings, 1970). Variability of both line spectrum and the continuum are generally distinctive features of Be stars. γ Cas was first observed spectroscopically in 1866 when Secchi (1867) noticed emission at Hβ in its spectrum. After 1927 almost every physical parameter of γ Cas was found to be variable. Physical parameters of γ Cas were estimated spectroscopically by Baldwin (1940). The two shell phases in 1935–36 and 1939–40, and the preceding intervals of enhanced emission lines, are well illustrated by Cowley and Marlborough (1968).

Several models have been constructed by Marlborough (1969), Hutchings (1970) and Poeckert and Marlborough (1978) to explain the behaviour of γ Cas. In this paper we report the stellar and envelope parameters of γ Cas estimated from the spectrophotometric scans.

2. Observations and Reductions

The scanner observations of γ Cas covering the wavelength interval λ350–700 nm were secured during 1977–78 on three nights (16 November, 1977; 13 October, 1978; and 30 December, 1978) with the 52-cm reflector of Uttar Pradesh State Observatory. The scanner consists of a Hilger Watts monochromator with a 600 lines mm^{-1} grating used in the first order, giving a dispersion of 7 nm mm^{-1}. An exit window of 0.7 mm admitting 5 nm of the spectrum was used. A cooled ($-20°$ C) EMI 9658B photomultiplier has been used as detector and standard d.c. techniques were employed for recording. β Ari, γ Gem and ϵ Per were observed as the standard stars and a comparison star together with γ Cas. The standard

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stars have been observed at nineteen discrete wavelengths between λ339–755 nm (Oke, 1965). The observations of each star were corrected for atmospheric extinction. The monochromatic instrumental magnitudes of γ Cas and ε Per thus obtained were reduced to absolute values with the aid of the standard stars. The absolute flux values correspond to the Hayes and Latham (1975) calibration of α Lyrae. The standard deviations of a single measurement on an individual night are $\pm 0^{m}.02$ in the wavelengths in excess of 403.6 nm and $\pm 0^{m}.03$ towards shorter wavelengths. The monochromatic magnitudes of γ Cas have been corrected for interstellar reddening, using the value of $E(B-V) = +0^{m}.18$ given by Hercot *et al.* (1978) and the interstellar reddening curve given by Schild (1977). The reddening-corrected monochromatic magnitudes of γ Cas normalized to the wavelength λ550 nm, together with the reddening corrections applied, have been given in Table I.

3. Stellar Parameters

3.1. Effective temperature and gravity

The effective temperature and gravity of γ Cas have been estimated by comparing the observed energy distribution curves with the appropriate blanketed model atmospheres (Kurucz *et al.*, 1974).

The observed energy distribution curves, corrected for interstellar reddening, were matched in the wavelength interval λ440–625 nm to the model atmosphere curves of different effective temperatures and gravities. The best match with an interpolated model having $T_{\mathrm{eff}} = 32\,000$ K and $\log g = 3.7$ has been shown in Figure 1. We have thus adopted $T_{\mathrm{eff}} = 32\,000$ K and $\log g = 3.7$ for the star. The estimated errors of these determinations are $\Delta T_{\mathrm{eff}} = \pm 2500$ K and $\Delta \log g = \pm 0.3$, respectively. γ Cas has a Balmer jump smaller than the normal star ε Per. This may be due to degradation of high-frequency quanta in the envelop of the star. Also, the Balmer jump is greater than that given by the model atmosphere because of the presence of the envelope, where hydrogen is not completely ionized.

3.2. Radius and mass

The radius of γ Cas has been determined with the aid of the relation (Gray, 1967)

$$\frac{R}{R_{\odot}} = \frac{44.33}{\pi} \times 10^{6} \left(\frac{F_{\nu}}{\mathcal{F}_{\nu}}\right)^{1/2}, \tag{1}$$

where π is the parallax of the star, and F_{ν} and $\mathcal{F}_{\nu}$ are the measured and best fitting model atmosphere fluxes, respectively. For the parallax π, we have used the spectroscopic parallax given by Lesh (1968). The mean radius determined at seven wavelengths is found to be $11 \pm 0.1\, R_{\odot}$. This uncertainty in the mean radius indicates that the radii are essentially uniform at the wavelengths con-

TABLE I

Reddening-corrected monochromatic magnitudes of γ Cas normalized to wavelength λ 550 nm along with reddening corrections

$1/\lambda$ (μm)$^{-1}$	λ(nm)	γ Cas 16 Nov., 1977 Standard (γ Gem) Mag.	13 Oct., 1978 Standard (β Ari) Mag.	30 Dec., 1978 Standard & comparison (= Gem and ϵ Per) Mag.	Reddening corrections Mag.
2.85	350	−0.25	−0.19	−0.37	0.92
2.77	360	−0.23	−0.19	−0.36	0.91
2.70	370	−0.20	−0.20	−0.33	0.89
2.63	380	−0.29	−0.30	−0.34	0.86
2.56	390	−0.44	−0.40	−0.42	0.84
2.50	400	−0.49	−0.48	−0.53	0.83
2.43	410	−0.56	−0.55	−0.56	0.81
2.38	420	−0.51	−0.50	−0.50	0.79
2.32	430	−0.47	−0.46	−0.46	0.77
2.27	440	−0.44	−0.43	−0.41	0.75
2.22	450	−0.41	−0.37	−0.40	0.74
2.17	460	−0.36	−0.34	−0.35	0.72
2.12	470	−0.32	−0.29	−0.28	0.71
2.08	480	−0.26	−0.27	−0.27	0.70
2.06	483.6	−0.25	—	−0.26	0.70
2.05	486.1	−0.28	—	−0.31	0.69
2.04	488.6	−0.24	—	−0.24	0.69
2.04	490	−0.22	−0.24	−0.22	0.68
2.00	500	−0.18	−0.20	−0.19	0.67
1.96	510	−0.17	−0.16	−0.14	0.65
1.92	520	−0.14	−0.13	−0.13	0.63
1.88	530	−0.10	−0.11	−0.10	0.61
1.85	540	−0.03	−0.09	−0.05	0.59
1.81	550	0.00	0.00	0.00	0.58
1.78	560	+0.01	0.00	+0.04	0.56
1.75	570	+0.02	+0.03	+0.03	0.54
1.72	580	+0.03	+0.02	+0.05	0.53
1.69	590	+0.12	+0.12	+0.11	0.52
1.66	600	+0.13	+0.13	+0.13	0.51
1.63	610	+0.26	+0.13	+0.17	0.50
1.61	620	+0.32	+0.15	+0.20	0.49
1.58	630	+0.34	+0.14	+0.18	0.49
1.56	640	+0.32	+0.12	+0.18	0.48
1.53	450	+0.31	+0.12	+0.16	0.47
1.52	653.8	+0.24	—	+0.10	0.47
1.52	656.3	−0.20	−0.18	−0.20	0.47
1.51	658.8	+0.25	—	+0.08	0.47
1.51	660	+0.32	+0.10	+0.13	0.46
1.49	670	+0.34	+0.09	+0.16	0.45
1.47	680	+0.36	+0.12	+0.15	0.45
1.44	690	+0.44	+0.04	+0.17	0.44
1.42	700	+0.45	+0.11	+0.16	0.43

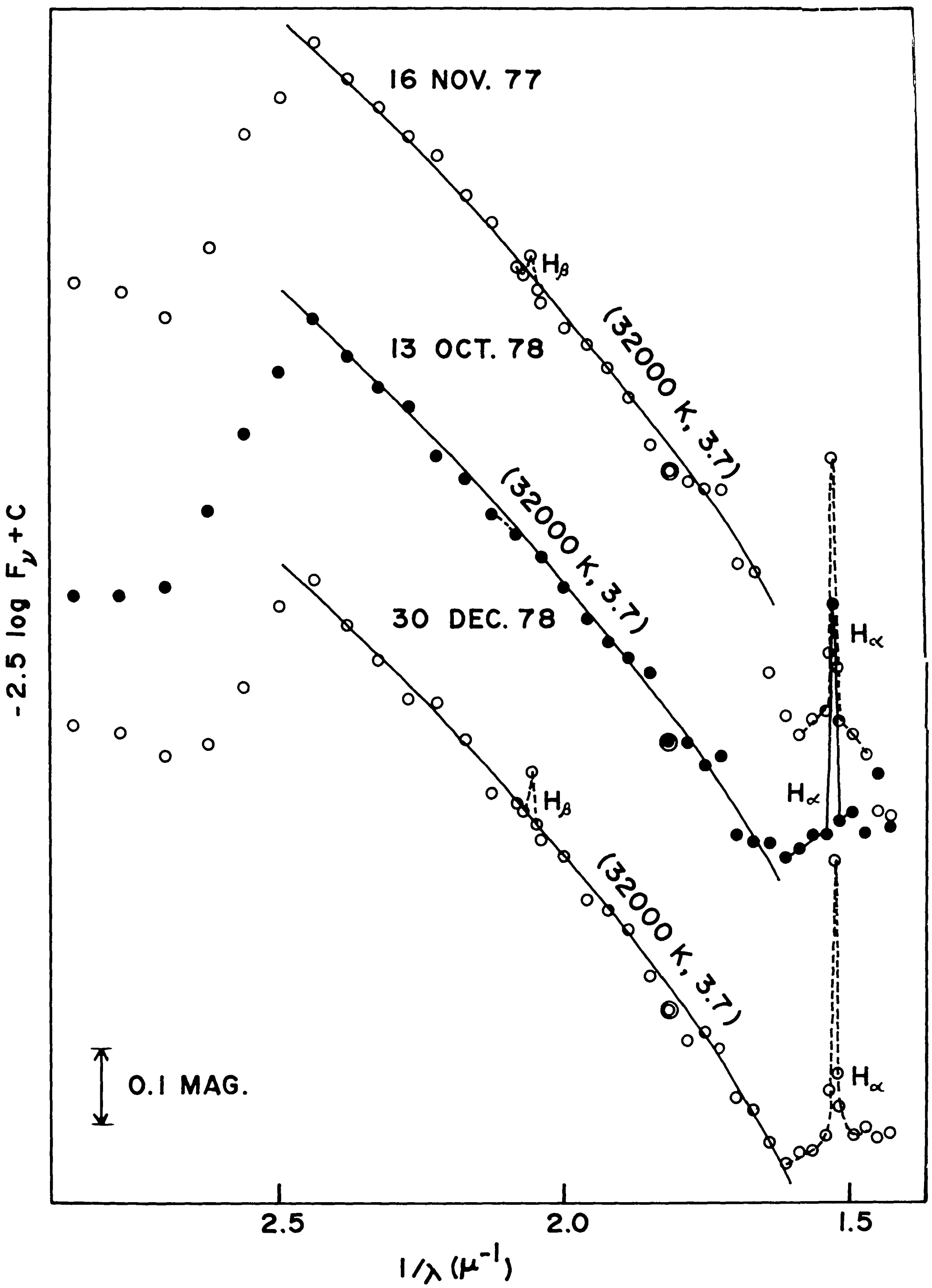

Fig. 1. Reddening-correct normalized energy distribution curves of γ Cas (open and filled circles) matched to a model (continuous curve) having a best fit. The normalization was performed at λ 550 nm (denoted by double circle).

sidered. The mass has been computed with the aid of the relation

$$\frac{M}{M_\odot} = \frac{g_{\text{eff}}}{g_{\text{eff}\odot}} \left(\frac{R}{R_\odot}\right)^2 . \tag{2}$$

Taking $\log g_{\text{eff}} = 3.7$ and $R = 11\ R_\odot$, we obtain $M = 25\ M_\odot$.

3.3 Effective temperature by Zanstra's method

The effective temperature has also been determined by Zanstra's method (Sobolev, 1960), by use of the relation

$$\text{H}\alpha = \frac{A_\alpha 8\pi^2 R^2 h\nu_{33}^4}{c^2} \frac{1}{(e^{h\nu_{23}/kT} - 1)}, \tag{3}$$

where Hα is the total energy emitted at the Hα line, which has been measured by comparing the comparison star ϵ Per with γ Cas and measuring the total area under the Hα emission line. The Hα and Hβ emissions above the continuum are shown separately in Figure 2. $A\alpha$ is Zanstra's quantity for the Hα line, which has also been measured from observations. Taking $R = 11\ R_\odot$ in Equation (3), we get $T_{\text{eff}} = 25\,000$ K for the star. This is low compared to the effective temperature

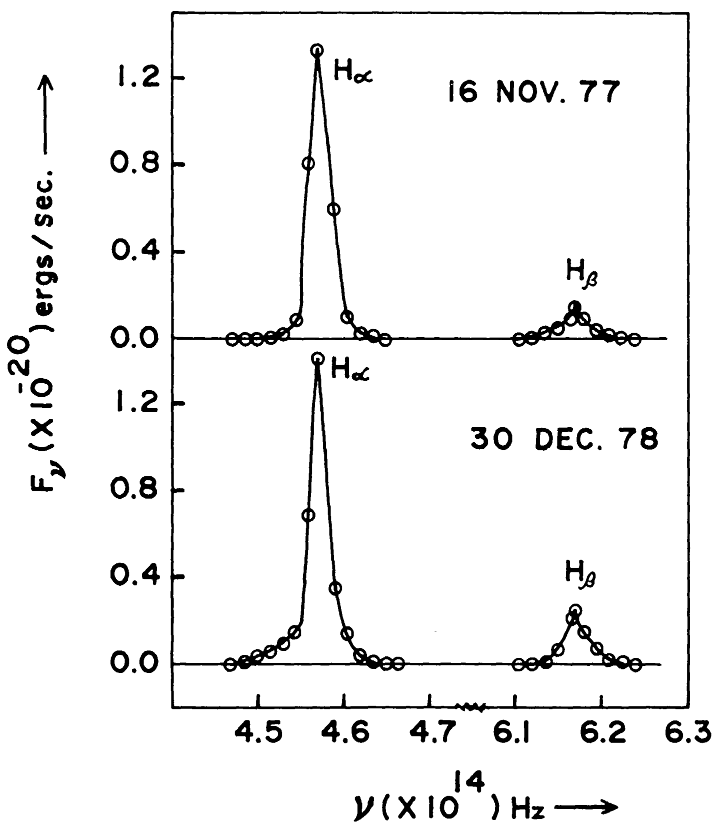

Fig. 2. Hα and Hβ emissions above the continum in γ Cas (dispersion 70 Å mm^{-1}). The ordinate represents energy emitted.

determined by the energy scans. However, this method is known to give a lower limit to the temperature.

3.4. Luminosity and Photospheric Electron Density

The luminosity of γ Cas has been determined using a measured apparent magnitude of 2.08, a parallax $\pi = 0.0052$ (Lesh, 1968) and an absorption of $0^{\mathrm{m}}.57$ (Schild, 1977). With these values we obtain $M_V = -4.74$. Applying a bolometric correction of $-3^{\mathrm{m}}.15$ given by Hayes (1978), we obtain $M_{\mathrm{bol}} = -7^{\mathrm{m}}.89$, which corresponds to $L = 10^5\, L_{\odot}$.

Many observers have discussed the problem of the luminosity of B and Be stars, and they generally agree that Be stars are slightly brighter than B stars. This may be due to emission from the envelopes surrounding Be stars.

It is well known that electron scattering plays an important role in the continuous absorption in the upper parts of Be stars. Therefore, by use of the relation (cf. Sobolev, 1960)

$$n_e^0 R = 0.5 \times 10^{24}, \tag{4}$$

and a star radius value of $R = 11\, R_{\odot}$, the photospheric electron density n_e^0 is found to be $\sim 6.5 \times 10^{11}\ \mathrm{cm}^{-3}$.

3.5. Mass-Ejection Rate

The mass-ejection rate per year ($\dot{M}$) has been estimated, using a radius of 11 $R_{\odot}$ and a photospheric electron density of $6 \times 10^{11}\ \mathrm{cm}^{-3}$, from the relation (Sobolev, 1960)

$$\dot{M} = 4\pi R^2 n_e^0 m_{\mathrm{H}} v \times 3.16 \times 10^7, \tag{5}$$

where v is the ejection velocity and m_{H} is the mass of a hydrogen atom. All Be stars are fast rotators, and mass-loss takes place along the equator due to reduced gravity, caused by the high equatorial rotational velocity. The mass-ejection velocity at the equator will be equal to the rotational velocity at the equator. Therefore, by adopting a value of $v = 569\ \mathrm{km\ s}^{-1}$ (Poeckert and Marlborough, 1978), we find the mass-ejection rate to be $\sim 7 \times 10^{-6}\, M_{\odot}\ \mathrm{yr}^{-1}$, which is of the order of the value given by Hutchings (1970) based on a steady-state stellar wind model.

4. Envelope Parameters

4.1. Extension of the Envelope and Electron Density in the Envelope

From the Balmer decrement (Hα/Hβ) determined from observations, a dilution factor (W) has been estimated (Kogure, 1959) as 0.023. The crude estimate of the envelope radius is made through the relation (Aller, 1954)

$$r \approx \frac{R}{2\sqrt{W}}. \tag{6}$$

TABLE II

Parameters for γ Cas

Stellar parameters	
Temperature (T_{eff})	32 000 K (from comparison with model)
	25 000 K (by Zanstra's method)
Gravity log g_{eff})	3.7
Radius (R)	11 $R_{\odot}$
Mass (M)	25 $M_{\odot}$
Luminosity (L)	$1 \times 10^5\ L_{\odot}$
Photospheric electron density (n_e^0)	6.5×10^{11} cm^{-3}
Mass-ejection rate ($\dot{M}$)	$7 \times 10^{-6}\ M_{\odot}$ yr^{-1}
Envelope parameters	
Extension of the envelope (r)	36 $R_{\odot}$
Electron density in the envelope (N_e)	6×10^{10} cm^{-3}
Electron temperature in the envelope (T_e)	12 000 K

The value of radius thus found is 36 $R_{\odot}$. The value of radius $r = 36\ R_{\odot}$ is used to estimate the electron density in the envelope through the relation (Kogure, 1961)

$$n_e = n_e^0 \left(\frac{R}{r}\right)^2. \tag{7}$$

By this formula we obtain $n_e = 6 \times 10^{10}$ cm^{-3}. This value of electron density lies in the range for Be stars given by Marlborough (1969).

4.2. Electron temperature

The envelope is assumed to be composed of ionized hydrogen. Since the ionization from only the second level plays the predominant part, the electron temperature has been estimated by graphical means based on the solution of the rêlation (Kogure 1961)

$$\frac{\int_{x_2}^{\infty} \frac{dx}{(e^x - 1)}}{\int_{x_2}^{\infty} \frac{dx}{x(e^x - 1)}} T_* = \frac{e^{-x_2}}{E_1(x_2)} (1 + 8\alpha_{ff} T_e) T_e. \tag{8}$$

The value of T_e is found to be ~ 12000 K.

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References

Aller, L. H.: 1954, *Nuclear Transformation, Stellar Interiors and Nebulae* (2nd edn), Vol. 2, Ronald Press, New York, p. 141.

Baldwin, R. B.: 1940, *Astrophys. J.* **92**, 82.

Cowley, A. P. and Marlborough, J. M.: 1968, *Publ. Astron. Soc. Pacific* **80**, 42.

Gray, D. F.: 1967, *Astrophys. J.* **149**, 317.

Hayes, D. S. and Latham, D. W.: 1975, *Astrophys. J.* **197**, 593.

Hayes, D. S.: 1978, in A. G. Davis Philip and D. S. Hayes (eds), 'The HR Diagram', *IAU Symp.* **80**, 65.

Hercot, D. M., Jamar, C., Momfils, A., Thompson, G. I., Houziaux, L. and Wilson, R.: 1978, Supplement to the *Ultraviolet Bright-Star Spectrophotometric Catalogue*, European Space Agency, SR-28, p. 6.

Hutchings, J. B.: 1970, *Monthly Notices Roy. Astron. Soc.* **150**, 55.

Kogure, T.: 1959, *Publ. Astron. Soc. Japan* **11**, 278.

Kogure, T.: 1961, *Publ. Astron. Soc. Japan* **13**, 335.

Kurucz, R. L. Peytremann, E. and Avrett, E. H.: 1974, *Blanketed Model Atmospheres for Early-Type Stars*, Smithsonian Institution, Washington, D.C.

Lesh, J. R. 1968, *Astrophys. J. Suppl.* **17**, 395.

Marlborough, J. M.: 1969, *Astrophys. J.* **156**, 135.

Oke: 1965, *Ann. Rev. Astron. Astrophys.* **3**, 23.

Poeckert, R. and Marlborough, J. M.: 1978, *Astrophys. J.* **220**, 940.

Schild, R. E.: 1977, *Astrophys. J.* **82**, 337.

Secchi, A.: 1867, *P. N.* **68**, 63.

Sobolev, V. V.: 1960, *Moving Envelopes of Stars*, Harvard University Press, Cambridge, Mass., p. 20.