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UV AND RADIOFREQUENCY OBSERVATIONS OF WOLF-RAYET STARS

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I. UV OBSERVATIONS WITH OAO-2

Very few observations are available. Of early rocket work on γ Vel (Stecher and Milligan 1962, Smith 1967) the most detailed spectra are by Stecher (1968) in the range $\lambda\lambda$ 1200 - 3100 A and by Carruthers (1968) in the range $\lambda\lambda$ 1050 - 1216 A. West's (1971) spectrum of γ Vel with the OAO-2 spectrometer (Code et al. 1970) in the range $\lambda\lambda$ 1050 - 2000 A appears to be somewhat different from Stecher's. Comparison must await full details.

The OAO-2 spectrometer has scanned apparently only one other W star, HD 50896. It is more informative than γ Vel because it is possibly a single star without contamination by a dominant O-star spectrum. It is also one of the WN5 stars in a symmetric nebula (cf. section II). Smith (1971) has reported the OAO-2 spectrum of HD 50896. Let us make a few more remarks about the same scans. First, the measured FWHM of the strong He II 1640 emission is $\Delta\lambda = 20$ A, or about 17 A after correction for instrumental broadening, in agreement with the ratio $\Delta\lambda/\lambda$ of fairly unblended lines at wavelengths several times larger. Thus Doppler broadening is confirmed. Second, interstellar hydrogen absorption at λ1215 A may be estimated from the 21-cm survey of McGee and Murray (1961): $N_H = 2.0 \times 10^{21}$ H atoms cm^{-2} toward HD 50896. Since the star is at $l = 234.°8$, $b = -10.°1$, and at the distance 1.59 kpc (Smith 1968b), most of the hydrogen should be in front of it. Morton's (1967) formula for the equivalent width $EW(Ly\alpha) = 7.31 \times 10^{-10} N_H^{\frac{1}{2}}$ (A) due to radiation damping of the interstellar line, then gives $EW(Ly\alpha) \lesssim 33$ A in absorption. As estimated from Figure 1 the net equivalent width of the features around $Ly\alpha$ is $\lesssim 30$ A in emission, so the net equivalent width of the features before interstellar absorption should be < 60 A in emission. Presumably the dominant emission near λ1215 A would be He II 1215, the second line in the series which He II 1640 heads. We estimate $EW(\lambda 1640) = 140$ A, a strength which appears to confirm the absence of continuum from any hot companion star.

The OAO-2 photometers (Code et al. 1970) have been used in the OAO-2 guest-investigator program to observe HD 192163. This WN6 star was selected because it is apparently a single star and it is in a symmetric nebula, NGC 6888 (cf. section II). In respect to the latter it may not be normal. The four photometers are each equipped with three filters. The range of effective wavelengths $\lambda\lambda$1330 - 3320 A is covered with passbands of FWHM = 240 - 860 A such that practically no gaps are left in the observed continuum. However, the data will tell little about a line spectrum. Figure 2 shows the observations. Figure 3 corrects them for interstellar extinction by means of the color excess E_{b-c} = 0.33 mag for HD 192163, and the ratio $E(B-V) = 1.6\ E_{b-c}$ (Smith and Kuhi 1970), and the average ultraviolet extinction $E(\lambda - V)/E(B-V)$ given by Bless and Savage (1971). There is still a question about the calibration of some of the photometer-filter responses (Bless 1971), but it is apparent that the run of the data corrected according to this differential extinction agrees rather well with an interpolated model atmosphere of $T_{eff} = 30700^{\circ}$K. This is the effective temperature for HD 192163 which Morton (1970) derived in a completely different way.

Ultraviolet spectral lines might have some effect on Figures 2 and 3, for example the strong line of EW(λ 1640) = 140 A such as HD 50896 exhibits. It would fall 40 A off center in the passband with $1/\lambda_{eff} = 5.95\ \mu^{-1}$ and FWHM = 270 A. It should therefore add close to 140/270 x 100 per cent = 52 per cent to the light of the continuum, but in fact this point falls low in the plots. We must conclude that He II 1640 is not prominent in HD 192163. C IV 1548 - 50 and N V 1238 - 42 fall in passbands with relatively high points in Figure 3, but we cannot claim the presence of these lines from the data.

Houck (1971) has made 200 OAO-2 spectrometer scans of β Lyr at 10 A resolution in the range $\lambda\lambda$ 1100 - 1800 A. He has found emissions of C IV, Si IV, and "Ly α" (the latter periodically shifted from interstellar absorption by orbital motion) in a spectrum which he compares with a star such as γ Vel.

Davis (1971) has presented preliminary photometry of about 500 stars observed with the Celescope on OAO-2. Two of them are W stars, CD-45°4482 and HD 76536. The new data are magnitudes called U1 and U2, respectively taken with passbands of 2100 - 3200 A and 1550 - 3200 A. Despite the gross passbands, additional information on effective temperatures of a few W stars should come out of the final catalog.

II. OBSERVATIONS OF W STARS WITH SYMMETRIC NEBULAE AROUND THEM

Johnson and Hogg (1965) used the Green Bank telescopes to detect NGC 6888 around HD 192163 at 750 MHz and 1400 MHz; also NGC 2359 around HD 56925 at 750, 1400, and 3000 MHz. The W stars are included with the nebulae in the available telescope beams but it has been assumed that the nebulae account for the observed flux densities. Johnson and Hogg (1965) reported the privately communicated independent discoveries by Herbig and by Minkowski of a third nebula 35' in diameter around HD 50896, which may be called S 308, but it was not detected in radiofrequency until later (Johnson 1971). Smith (1967, 1968a) searched Palomar Sky Survey charts and other material, discovered four more symmetric nebulae around W stars, and noted that all seven stars were WN5, 6, or 8 types. Smith and Batchelor (1970) proceeded to observe three of them, NGC 3199, RCW 104, and RCW 58 at 11 cm. Lozinskaya (1970), Terzian (1970), and Johnson (1971) observed NGC 6888 again at 8500, 318, and 7795 MHz, respectively. The radiofrequency spectrum of NGC 6888 is shown in Fig. 1. It is apparently thermal Bremsstrahlung.

These radiofrequency data, or alternatively the integrated flux of the nebula in a Balmer line, corrected for extinction, such as Parker (1963) has estimated only for NGC 6888, with a distance estimate of the W star, lead to the mass of the nebula and to the "excitation parameter" U of the star, or to the equivalent spectral type and effective temperature. The "Zanstra temperature" of W stars is also obtained if the stellar magnitude, rather than the distance, is employed with the nebular flux density. Morton (1970) refined the Zanstra method by calculating model atmospheres in place of blackbodies, and he found effective temperatures as a function of W-star types. By including the observed angular size we also get the linear dimensions and a confirmation of the mass distribution (thin-wall shell appearance on photographs). Finally, observations of the internal motions of the nebula may be combined with observations of the rate of mass loss and ejection velocity from the W star, and with an estimate of ambient interstellar density, in order to obtain the age of the system.

Conservation of momentum and continuous ejection were assumed in the simple theory (Johnson and Hogg 1965). Spherical symmetry was also assumed, tacitly contrary to the observed ellipticity of the nebulae, eccentricity of stellar site, and correlated azimuthal asymmetry of nebular perimeter (brightest nearest the star). In apology one can only say that these nebulae are quite symmetrical in comparison with ordinary diffuse nebulae, and perturbations that are attributable to a stellar or interstellar magnetic field, or to irregularity of ambient interstellar density, appear to be negligible in the first objectives of the theory. The higher degree of central-star concentricity which prevails in planetary nebulae may be explained by their smaller radii, statistically higher z-distances, and consequent lack of interaction with the ambient medium. However, the non-circular projection of many planetary nebulae shows that central stars do not eject mass isotropically.

The full application of these ideas has been made only to NGC 6888, the W-star nebula in which large nebular velocities are observed (Courtès 1960, Lozinskaya and Esipov 1968, Lozinskaya 1970, and Georgelin and Monnet 1970). The result is a self-consistent picture of a single WN6 star with the effective temperature of about 31000°K, which for unknown reasons ejects mass at a velocity of 1400 km/sec and rate of 10^{-5}- 10^{-6} $M_{\odot}$/year into collision with an ellipsoidal nebular shell of projected dimensions 12' x 18'. If the distance is 1.2 kpc the mean radius of the shell is 2.6 pc, which is considerably larger than the shells of planetary nebulae. Smith (1968b) finds the distance to be 2.29 kpc, but this summary is based on the smaller distance. The mean linear thickness of the nebula is only 10^{-2} pc (shell walls); its electron density is 400 cm^{-3} and electron temperature is 15 - 19 x 10^3 °K. The shell is expanding 50 - 80 km/sec and sweeping up interstellar matter with a density of about 1 - 2 cm^{-3}. The age is about 2 x 10^4 years if the ejection and transfer of momentum has been steady.

The shell mass is about 4 $M_{\odot}$ of which only 3 per cent has been contributed by the ejecta of the W star. Thus the element abundances inferred from the stellar spectrum of HD 192163 need not agree with those inferred from the nebular spectrum (normal). The excitation of the shell appears to be radiative, not collisional.

Before these investigations NGC 6888 was classified as a supernova remnant (e.g. Pikelner 1959, Lozinskaya and Esipov 1968) or as a "giant planetary nebula" (e.g. Parker 1964). Minkowski (1965) has suggested also that S 308, the shell around HD 50896, is possibly a planetary nebula. Lozinskaya and Esipov (1968) and Georgelin and Monnet (1970) agree that the mean radial velocity of NGC 6888 is -50 km/sec; no rms error is given. (Lozinskaya and Esipov also estimated the radial velocity of HD 192163 equal to -120 ± 20 km/sec, despite the difficulty of the broad spectral lines.) The galactic coordinates are $l = 75^{\circ}.5$, $b = +2^{\circ}.4$, the component of differential galactic rotation is +7 km $sec^{-1} kpc^{-1}$, and the component of solar motion with respect to the local standard of rest is 18 km/sec toward HD 192163. Hence one component of the velocity of the nebula with respect to its local standard of rest is probably -41 to -49 km/sec at distances of 1.2 - 2.3 kpc. Of course, the near side of the nebula may contain most of the observed filaments. If not so, the mean velocity is appropriate to a "runaway" O star or a planetary nebula.

In view of the high dispersion of velocities in NGC 6888, it is interesting that three other examples do not show it. They are given in Table 1 and their velocity dispersions do not differ significantly from those in ordinary nebulae. Successive columns give the nebula, its radius in arc minutes and in pc according to the spectroscopic distance, its mass (Smith and Batchelor 1970), the rms σ of n velocities in the nebula (Georgelin and Georgelin 1970), the included star, its spectral type, its spectroscopic distance R(sp)(Smith 1968b), and the kinematic distance of the nebula R(kin)(Georgelin and Georgelin 1970). If the theory which has been applied usefully to NGC 6888 is applied to the objects of

Table 1, one must conclude that these nebulae have become massive and the velocities of the shells have slowed down to ordinary internal motions in nebulae, because they are older than NGC 6888. For conventional values of the parameters, e.g. rate of mass loss = 10^{-5} $M_\odot$/year, velocity of ejection = 10^3 km/sec, and interstellar density = 1 hydrogen atom cm^{-3}, the derived ages are 2 - 20 x 10^5 years, or 10 - 100 x the age of NGC 6888. The difficulty is that WN6 stars apparently survive 2 x 10^6 years if HD 192163 and HD 147419 are equal members of the class WN6. But the total mass loss is 20 $M_\odot$ at this age, and the mass of WN5-6 stars in binary systems is about 11 $M_\odot$ (Smith 1968a). A reduction in rate of mass loss by a factor of 10 increases age by about $\sqrt{10}$ so that the total mass loss is then 6 $M_\odot$ rather than 20 $M_\odot$. An increase of ambient density outside the shell by a factor of 10 also increases age by about $\sqrt{10}$.

The mass of RCW 58 is estimated to be small, 5.7 $M_\odot$ (Smith and Batchelor 1970), and likewise the mass of S 308 to be only 3 $M_\odot$ (Johnson 1971). They are candidates for large expansion velocities but they have not been observed with the interferometer. Neither has any symmetric nebula around a W star been reported in the radiofrequency H recombination lines. It is reasonable to consider measuring proper-motion expansions in NGC 6888 and S 308, but RCW 58 may be too small for the scale of available plates. At present we tentatively conclude that the less massive nebulae of the class we have discussed are the younger, and that the best-studied member of the class, NGC 6888, may be peculiar as well as young.

If we accept the theory of ejected stellar mass sweeping out a volume of ambient interstellar gas around some W stars, and note the result that the star contributes only a few per cent of the total mass in each case, we may derive the ambient interstellar density $\underline{N}_H$ of the swept volume. This is, first, a check on self-consistency of the theory for which Johnson and Hogg (1965) originally had to estimate $\underline{N}_H$ independently in order to establish the theory;

and, second, it makes possible some comparisons with the rival suggestion that the gas in a symmetric nebula has been ejected from the star at some earlier stage of evolution (e.g. red giant) and said gas might have no dependence on current mass-loss in the W star. The four nebulae of Table 2 are the only ones for which the symmetric-nebular mass M has been derived from the spectroscopic distance $\underline{R}$, the observed flux density, and the observed nebular gas density $\underline{N}_e$ via the method of the [O II] 3726-29 doublet-ratio. If the gas is non-uniform, $\underline{N}_e$ is overestimated and M and $\underline{N}_H$ are underestimated. We draw the following conclusions from the table: First, there is an apparent dependence of $\underline{N}_H$ on the $\underline{z}$-distance from the galactic plane, in the sense expected of swept interstellar gas rather than of a mass entirely derived from the star during stellar evolution. Second, $\underline{N}_H$ is a factor of 10 greater than mean interstellar densities, so that an association of W stars with denser clouds is implied. Alternatively, we could say that $\underline{N}_H$ decreases from type WN5 to type WN6, and the absolute density is governed by factors other than ambient interstellar mean density to make it greater than the mean. At present the interstellar density near specific W stars is not well enough known independently to decide.

It is interesting to ask about the visibility of the ejecta of W stars before any effects of collision with ambient interstellar matter. If the velocity of the mass lost at radii $\underline{r} \gtrsim 30\ \underline{R}_\odot = 7 \times 10^{-7}$ pc is constant, then electron density $\underline{N}_e(\underline{r}) \propto \underline{r}^{-2}$. If $\underline{N}_e = 10^{12}$ cm^{-3} at $\underline{r} = 30\ \underline{R}_\odot$ the hydrogen emission measure $EM = \int \underline{N}_e(\underline{s})\underline{N}_H(\underline{s})d\underline{s}$ may be computed along lines of sight which pass ρ pc from W stars. In the approximation that ρ is small compared with the distance of the star, $EM = 0.12\pi\rho^{-3}$ pc cm^{-6}. For example, at $\underline{R}$ = 1200 pc, EM = 1.9×10^6 pc cm^{-6} at 1" arc from the star, or 1.9×10^3 pc cm^{-6} at 10" arc. Nebulae for which EM $\gtrsim$ 400 pc cm^{-6} are commonly visible on Hα photographs. However, the star image would be competitive on ordinary photographs, and the hydrogen emission measure would not be appropriate for hydrogen-deficient W stars. According to

Pengelly (1964) the intensity of recombination He II 6560 is 0.6 x the intensity of Hα in the limit of a low electron density and at $T_e = 10^4$ °K. Likewise the intensity of He II 4686 is 4.4 x the intensity of Hα. We should probably find $N_e = 2\, N_{He^{2+}}$ rather than $N_e = N_{H^+}$ in the envelopes of some W stars. Note also that, according to the adopted density law, $N_e < 10^{10}$ cm^{-3} at $r \geq 300\, R_\odot$, and forbidden lines can be emitted. They may compete with He II lines in intensity as in planetary nebulae.

But one more question remains about the expanding envelope of a W star regarded as a special H II region. Is the Strömgren radius r_s significantly larger than the star? Can the continuum photons of the core below λ912 A escape to photoionize the symmetric nebulae? If the envelope density $N_e = 10^{12}$ cm^{-3} is constant inward from $r = 30\, R_\odot$ to the photosphere of a star of radius $r_* = 6\, R_\odot$ and effective temperature of 30000°K, $r_s = 29\, N_e^{-2/3}$ pc $= 2.9 \times 10^{-7}$ pc $= 13\, R_\odot$, as given by Spitzer (1968) for a standard O8 star. The actual radius r_s will be larger if the W-star core is larger or hotter or if N_e is less. However, N_e may be greater since the possible range is $10^{10} - 10^{14}$ cm^{-3} (Underhill 1968), and the density may follow the r^{-2} law for constant-velocity ejection down to the photosphere. Doubly-ionized He regions are smaller than ionized H regions. Detailed models are in order, but an immediate conclusion is that some W envelopes may smother the stellar uv radiation, unless the envelopes are confined to the equatorial plane or some other non-isotropic configuration. We should be tempted to explain in this way the absence of symmetric nebulae or other nebulae around some W stars except for the complication that they may be doubles with companions that are independently able to photoionize surrounding nebulae.

Are W stars or their expanding envelopes detectable as radio sources? Davies et al. (1967) reported HD 16523 and HD 193793 at 2695 MHz in a beam of 15' HPBW. However, the former source is probably identifiable with 4C56.04

rather than the W star (Johnson 1971), and no W star has been detected in a search with the Green Bank interferometer (Hjellming 1971). Johnson (1971) looked at HD 9974, HD 168206, HD 177230, HD 187282, HD 190918, HD 191765, HD 193793, HD 211853, and HD 214419 at 7795 MHz in a beam of 4.4 HPBW. One source was found in the beam at HD 211853, but this is probably part of a (non-symmetric) nebula in the area. The answer to the question appears to be no at present.

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TABLE 1

SYMMETRIC NEBULAE WITH SMALL DISPERSIONS OF VELOCITY

Nebula	Radius		M	σ	n	Star	Sp.	R(sp)	R(kin)
	(' arc)	(pc)	(⊙)	(km/sec)				(kpc)	(kpc)
NGC 2359	4*	8*	330*	8.0	29	HD 56925	WN5	6.92	4.57
NGC 3199	8	8	400	6.5	33	HD 89358	WN5	3.63	†
RCW 104+106	10	18	650	8.0‡	60‡	HD 147419	WN6	6.31	3.75

*Pertains to the sharp inner ring of the nebula.

†Differential galactic rotation at $l = 283\overset{\circ}{.}5$ is too small for a significant kinematical solution.

‡Data for both nebulae.

TABLE 2

INTERSTELLAR DENSITIES NEAR W STARS

Nebula	Star	Sp.	R(sp) (kpc)	z (pc)	r (pc)	N_e(sp) (cm^{-3})	M (⊙)	N_H (cm^{-3})
NGC 2359	HD 56925	WN5	6.92	12	8*	100*	330*	4.7
NGC 3199	HD 89358	WN5	3.63	63	8	240	400	5.7
NGC 6888	HD 192163	WN6	2.29	96	5	400	21	1.2
RCW 104	HD 147419	WN6	6.31	165	18	190	650	0.8

*Pertains to the sharp inner ring of the nebula.

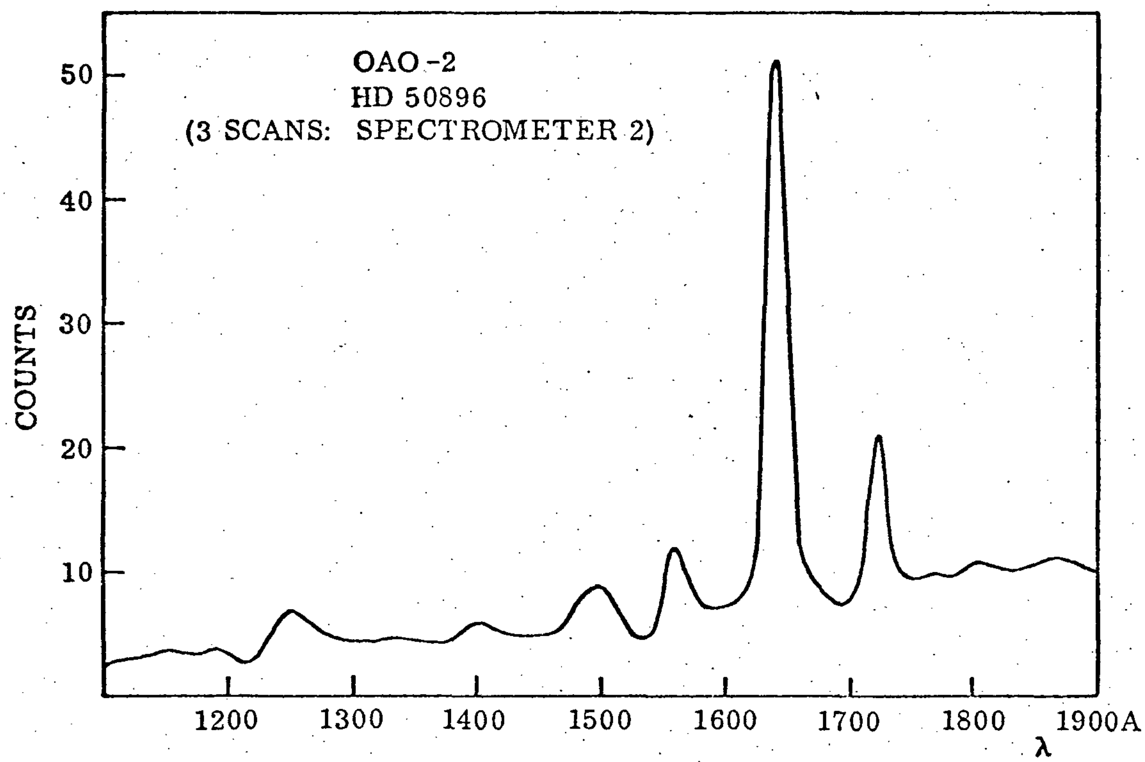
CAPTIONS

Figure 1.--Scanned spectrum of the WN5 star HD 50896.

Figure 2.--Photometered spectrum of the WN6 star HD 192163, with intensity per unit wavelength I_λ normalized to an arbitrary zero-point at λ3320 A. The first set of data has 12 solid points; the second has 9 open circles.

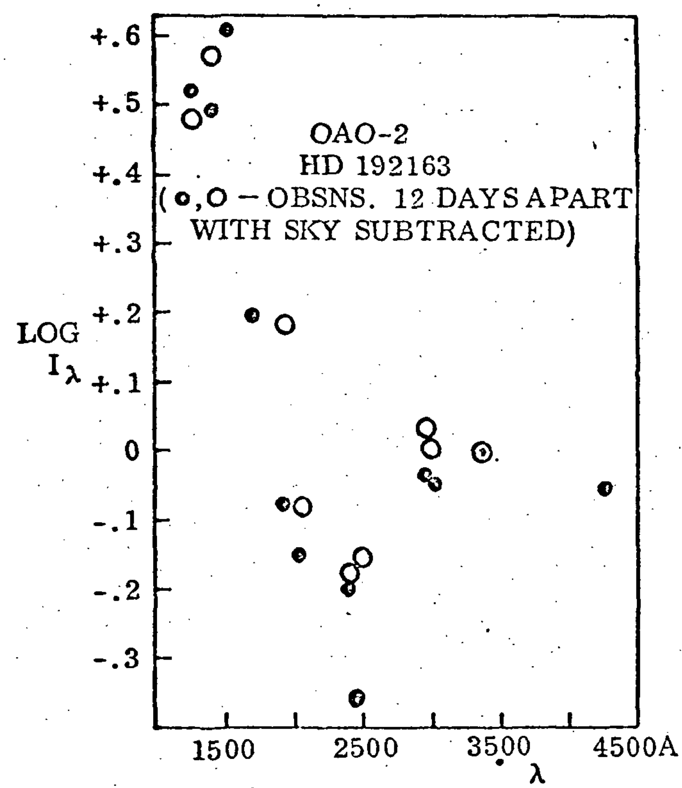
Figure 3.--Mean data of HD 192163 (points) in Figure 2 reduced to intensity per unit frequency, corrected for interstellar extinction, and compared with two model O-type atmospheres (labeled curves) by Bradley and Morton (1969). Dr. Morton suggested the comparison with these models. The zero-point of observed intensity is fitted arbitrarily to the scale f_ν of the curves.

Figure 4.--Radiofrequency spectrum of NGC 6888. Unit flux density (f.u.) = 10^{-26} Wm^{-2}Hz^{-1}. The observed data are by Johnson and Hogg (1965) J-H, Lozinskaya (1970) L, Terzian (1970) T, and Johnson (1971) J.



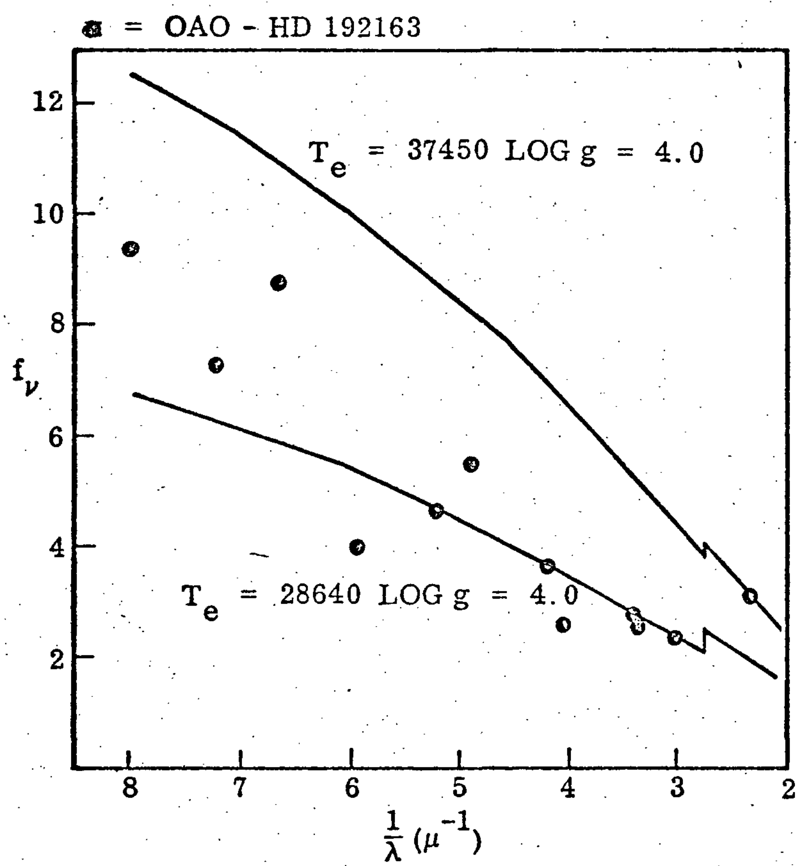
OAO-2
HD 50896
(3 SCANS: SPECTROMETER 2)
50
40
30
20
10
COUNTS
1200
1300
1400
1500
1600
1700
1800
1900A
λ

Fig. 1



OAO-2
HD 192163
(•,O – OBSNS. 12 DAYS APART
WITH SKY SUBTRACTED)
+.6
+.5
+.4
+.3
+.2
+.1
0
-.1
-.2
-.3
LOG
I_λ
1500
2500
3500
4500A
λ

Fig. 2



= OAO - HD 192163
12
10
8
6
4
2
f_ν
T_e = 37450 LOG g = 4.0
T_e = 28640 LOG g = 4.0
8
7
6
5
4
3
2
$\frac{1}{\lambda}$ (μ^{-1})

Fig. 3

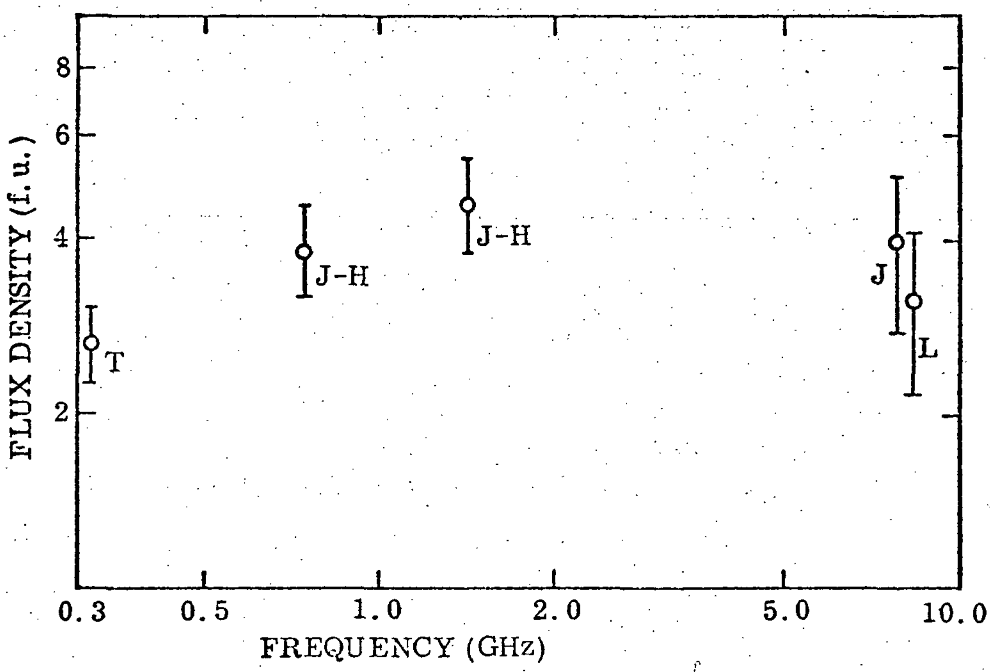


Fig. 4