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SPECTROPHOTOMETRIC OBSERVATIONS OF THE COMPACT H II REGION K3-50 AND OF NGC 6857

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ABSTRACT

Spectrophotometric observations of K3-50 from 0.5 to 1.1 μ demonstrate that there is a discrepancy between the values of the interstellar extinction determined from radio, infrared, and optical measurements. The optically determined value for the visual absorption A_V is 8.3 mag, considerably less than the values derived by comparing the Hα or 1.65-μ flux with the 10-GHz flux. A model consistent with the data involves spatially varying extinction which affects one or more sources unequally.

The region K3-50 also has a prominent optical continuum which is interpreted as arising from an early-type star or stars. The bolometric luminosity of this star is shown to be comparable to the far-infrared luminosity of K3-50.

Similar observations of the nearby nebula NGC 6857 show that it differs in several respects from K3-50. In particular, the extinction toward NGC 6857 is considerably less than that observed toward K3-50.

Subject headings: infrared sources — interstellar reddening — nebulae — nebulae, individual

I. INTRODUCTION

The complex emission region W58 which includes the optical nebulae K3-50 and NGC 6857 (Sharpless 100) has been studied at optical, infrared, and radio wavelengths (Rubin and Turner 1969, 1971; Neugebauer and Garmire 1970; Wynn-Williams 1969; Higgs 1970; Bridle and Kesteven 1970; Harper and Low 1971; Gillett, Forrest, and Merrill 1973; and de Jong and Lo, private communications). K3-50 is a compact H II region located within a massive H I complex. It is of particular interest because it is an optical source whose spectrum may be studied in relation to its radio and infrared emission. This spectrum is characterized by low excitation, similar to those of galactic H II regions, and heavy interstellar extinction. The infrared energy distribution of K3-50 increases rapidly toward longer wavelengths—it emits 180 f.u. at 10 μ. This emission (far in excess of that expected from free-free emission) is due to thermal radiation from heated dust grains.

The published data reveal the following properties: $N_e > 2 \times 10^4$ cm^{-3}; the emission measure $> 1.4 \times 10^7$ pc cm^{-6}; the angular size is $< 7''$ at 5 GHz, $< 3''$ at 3.6 μ and appears stellar in the optical. The positions of the radio, infrared (1.65–10 μ), and optical sources agree to within 2″ or 3″. The indicated kinematic distance is 8.8 kpc, but could be considerably less. The far-infrared flux as measured with a beam diameter of 8′.4 gives a total luminosity of $L/L_\odot = 1.3 \times 10^6 (D/8.8\text{ kpc})^2$. This is an upper limit to the far-infrared luminosity of K3-50 itself.

In this paper we present spectrophotometric data on K3-50 from Hβ (λ4861) to 1.1 μ. These optical data are important because they allow a direct determination of the amount of interstellar reddening, the strength of the continuum, and the flux due to recombination lines of hydrogen. We also present similar optical data for NGC 6857, a nebula about 1′ south of K3-50.

II. OBSERVATIONS

The observations were made in 1972 September with the multichannel spectrometer (Oke 1969) on the 200-inch (5-m) Hale telescope. A detailed account of the observing procedure will be published separately. Briefly, the instrument was configured to accept radiation in certain specially made emission-line exit slots. Four grating positions sufficed to measure a number of emission lines and several neighboring line-free continuum points. The use of a 3″.6 diameter entrance aperture ensured that there was no line blending that could not be deconvolved in a straightforward and anticipated manner, and that each exit slot accepted all the light from the emission-line image of the entrance aperture in the exit plane.

The television guiding system was used to find and guide on the optical image of K3-50 as identified by Rubin and Turner (1971). The sky signal was simultaneously recorded in all channels from a point 40″ west of K3-50, a region of emission judged to be far weaker than K3-50 itself. The seeing was ~1″, and ensured that light from stars near the apertures did not contaminate the signals. This was confirmed by the consistency of the continuum sky counting rates with those measured at other (dark) locations in the sky. As the data were being recorded, we confirmed that K3-50 was very heavily reddened, and found that a prohibitive amount of observing time would have been required to measure the blue region of the

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spectrum properly. We thus have data only for $\lambda >$ 4800 Å. Since the same integration time was spent on each line, the photometric accuracy varies greatly from one line to another. Furthermore, since K3-50 is located in an emission region that is considerably less heavily reddened, background emission entering the line sky channels is relatively enhanced in the blue. A sizable dark count in the Hβ channel and an uncertainty in the underlying blue continuum serve to make the Hβ flux somewhat uncertain.

The data for K3-50 and NGC 6857 were reduced in the standard fashion (using the calibration of Oke and Schild 1970), except that the fluxes from K3-50 were scaled up by a factor of 1.25 to take account of seeing losses. This factor was determined from multi-aperture observations of a nearby star, and was wavelength-independent. No seeing correction was applied to NGC 6857, as it is considerably larger than the entrance aperture. Since the objects were observed at the zenith, no correction for differential refraction was necessary.

III. RESULTS

a) K3–50

The results of the observations are presented in tables 1 and 2 and in figure 1. In order to find the line fluxes, the underlying continuum level must be determined. A least-squares fit to the continuum (measured in line-free bands) was used above 7000 Å, and a fit by eye below 7000 Å. Uncertainty in the level of the continuum contributes to the errors in the line fluxes. The observed points and fitted continuum are shown in figure 1.

Table 1 lists the lines positively detected on a scale for which $I(\mathrm{H}\beta) = 100$ both before and after correcting for reddening (see below). The estimated uncertainty σ_m is 1 σ of the mean found from the individual measurements or from counting statistics, whichever is larger, and is referred to the intensity corrected for reddening. The flux values at $F(\mathrm{H}\beta) = 1.8 \pm 0.6 \times 10^{-14}$ (observed) and $1.3 \pm 0.4 \times 10^{-10}$ (corrected for extinction) ergs cm^{-2} s^{-1}.

Table 2 lists the values of the reddening constant $C \equiv \Delta \log I(\mathrm{H}\beta)$ found from the ratios of the observed hydrogen lines and the color of the continuum as discussed below. The reddening function used was that given by the van de Hulst curve No. 15 (Johnson 1968), and the recombination values of the line ratios are those of Brocklehurst (1971) for $T_e = 10^4$ ° K. The differences in the values of C will be discussed below; the ratio of Paschen 7 (λ10,049) to Hα gives the most reliable value of C, viz., 3.8. This corresponds to a visual extinction of 8.3 mag.

Figure 1 shows the atomic continuum, computed from the tables of Brown and Mathews (1970), predicted from the observed value of $I(\mathrm{H}\alpha)$; we used $T_e = 10^4$ ° K, $N(\mathrm{He}^+)/N(\mathrm{H}^+) = 0.15$, $N(\mathrm{He}^{++}) = 0$, and $C = 3.8$. A value of $N_e = 10^4$ cm^{-3} was assumed to determine the two-photon contribution. The important result is that the observed continuum is significantly stronger than that expected from the nebular continuum alone. This result agrees with the appearance of the spectrum of Rubin and Turner (1971). The observed excess continuum flux at 1 μ is $4.5 \pm 1.0 \times 10^{-26}$ ergs cm^{-2} s^{-1} Hz^{-1}, and we attribute it to radiation from the exciting star or stars. The last value of C in table 2 was derived by assuming that the stellar radiation may be characterized by a 40,000° K blackbody between 6000 and 11,000 Å. Since we are in the Rayleigh-Jeans region of the spectrum for any reasonable exciting star, the value of C so derived will be insensitive to the stellar temperature. Table 2 shows that this value of C agrees with the values derived from the recombination lines. Thus, in the spectral region between 6000 and 11,000 Å the wavelength dependence of the reddening is consistent with that given by van de Hulst's curve No. 15, which is essentially the Whitford reddening law.

The abundance of helium as given by $I(\lambda 5876)/I(\mathrm{H}\beta)$ is 7 ± 4 percent by number, consistent with the radio

TABLE 1

SPECTROPHOTOMETRY OF K3-50 AND NGC 6857

		K3-50			NGC 6857		
λ	IDENTIFICATION	Observed Intensity	Corrected Intensity	σ_m	Observed Intensity	Corrected Intensity	σ_m
3727.........	[O II]	...	...	...	18	73	50
4340.........	H I	...	...	...	24	45	13
4861.........	H I	100	100	30	100	100	6
4959.........	[O III]	54	41	10	144	128	5
5876.........	He I	71	10	3	39	14	3
6563.........	H I	2620	136	15	1308	287	3
6584.........	[N II]	806	40	6	71	15	2
7065.........	He I	119	3	1	14	2.2	1
7325.........	[O II]	522	10	3	...	...	...
7751.........	[A III]	...	...	...	29	3	1
9015.........	H I	239	1.2	0.4	41	2.7	1
9069.........	[S III]	4220	20	5	621	40	2
10049.........	H I	961	2.4	0.3	151	7	1
10830.........	H I	20400	36	4	741	29	15

TABLE 2

REDDENING VALUES

K3-50			NGC 6857		
Ratio	C*	σ_m	Ratio	C	σ_m
10 GHz/1.65 μ..........	>9.9	...	P7/Hβ..............	2.15	±0.07
10 GHz/P7............	8.8	...	P10/Hβ.............	2.26	0.13
10 GHz/Hα............	6.3	...	Hα/Hβ..............	1.98	0.03
1.65 μ/Hα..............	5.5	...	Hγ/Hβ..............	2.07	0.11
P7/Hα................	3.8	±0.2			
P10/Hα................	4.1	+0.4/−0.3			
10 GHz/Hβ............	5.2	...			
Hα/Hβ................	2.9	+0.5/−0.3			
Continuum.............	4.1	+0.4/−0.3			

* $C \equiv \Delta \log I(\mathrm{H}\beta) = A_V/2.17$.

determination (Chaisson and Goad 1972). From the nondetection of He II λ10,120, a 3 σ upper limit of $N(\mathrm{He}^{++})/N(\mathrm{H}^+) \leq 0.005$ is found. The ratio $I(\lambda 10{,}830)/I(\lambda 5876)$ is lower than the expected value of ~10 for $N_e \simeq 10^4$ cm^{-3} and $T_e \simeq 1.0$–1.5×10^4 °K. This would indicate that resonance-line trapping and destruction on the dust grains is operating (cf. Persson 1970).

In addition to the lines given in table 1, several other emission lines were detected but had large errors (e.g., H I λ8863), and others were found to be absent ([O I] λ6363, [S II] λ6312, [N II] λ5755, He II λ10,120). Paschen 8 (λ9540) is blended with [S III] λ9536 and both were omitted from the table.

b) NGC 6857

A condensation 14″ south and 5″ west of the bright star in the center of NGC 6857 was measured for comparison with the spectrum of K3-50. Tables 1 and 2 give the results of the observations. No attempt was made to measure the continuum completely as it is considerably weaker relative to that in K3-50. The Hβ surface brightness is $4.3 \pm 0.3 \times 10^{-13}$ ergs cm^{-2} s^{-1} (arc sec)$^{-2}$, corrected for extinction.

The following summarizes the observational results for NGC 6857: (*a*) NGC 6857 is not nearly as heavily reddened as K3-50; table 2 shows agreement at the 2 σ_m level between the values of C computed from hydrogen-line ratios, viz., $C = 2.0 \pm 0.1$. (*b*) The excitation of the nebula is higher than that of K3-50; for example, $N(\mathrm{N}^+)/N(\mathrm{H}^+)$ is very low, and $N(\mathrm{S}^{++})/N(\mathrm{H}^+)$ and $N(\mathrm{O}^{++})/N(\mathrm{H}^+)$ are higher than in K3-50, if the temperatures are similar. (*c*) The He$^+$ abundance is 10 percent by number. The He^{++} abundance is low, but a good upper limit cannot be calculated from the data. It seems likely that the ratio $I(\lambda 10{,}830)/I(\lambda 5876)$ is lower than expected for an H II region, but the data do not allow a proper evaluation of the ratio. (*d*) The relative strengths of the lines are in agreement with the spectrum published by Rubin and Turner (1971).

IV. THE LUMINOSITY OF THE EXCITING STAR(S) IN K3-50

The measured stellar flux at 1 μ can be used in a discussion of the energetics of K3-50. Since not all of the stars exciting K3-50 may be included in a 3″.6 aperture, the measured 1-μ stellar flux is a lower limit

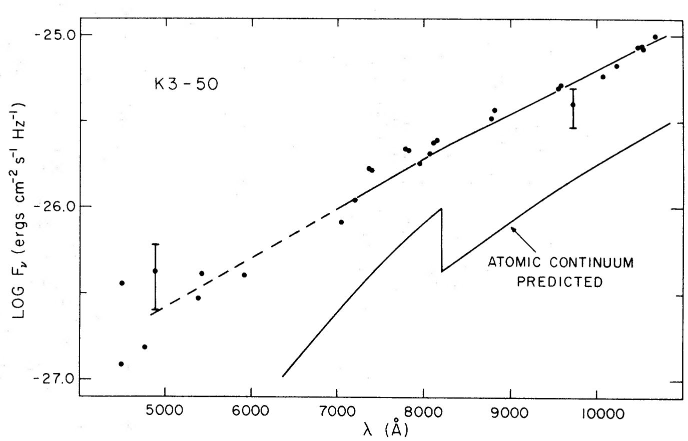

FIG. 1.—The continuous energy distribution of K3-50. Typical 1 σ_m error bars for the green and red spectral regions are shown. The parameters used in computing the predicted atomic continuum were: $T_e = 10^4$ °K, $N_e \simeq 10^4$ cm^{-3}, F(Hα, observed) = 4.75×10^{-13} ergs cm^{-2} s^{-1}, $N(\mathrm{He}^+)/N(\mathrm{H}^+) = 0.15$, $C = 3.8$. The size of the errors do not rule out the presence of a weak Paschen jump, which has been ignored in drawing the fitted continuum.

to the total stellar flux available and gives $M_V < -1.9\text{–}5 \times \log D(\text{kpc})$ for a typical hot-star energy distribution. We have assumed a normal reddening law and no forward scattering (see § V). If K3-50 is 8.8 kpc distant, M_V represents either one star half a magnitude brighter than the mean value for an O4 star (Conti 1973), or a cluster of about five O6 stars. In either case, this lower limit to the available ionizing photon luminosity and total bolometric luminosity is consistent with the requirements of the radio flux and the total flux from 50 to 350 μ (Harper and Low 1971), respectively. If, on the other hand, the object is, say, only 2.5 kpc distant, $M_V < -3.9$ (spectral type O8). The far-infrared luminosity and the radio flux are again consistent with such a star. Thus, for either distance, the observed 1-μ stellar flux and inferred spectral type predict both a total luminosity which is sufficient to account for the far-infrared luminosity (the bulk of the emission) and the proper number of ionizing photons to account for the 10-GHz measurement. This result is similar to that found by Johnson (1973) for several other H II regions. Taken at face value, then, the data indicate that a significant fraction of the total stellar emission at 1 μ is in fact being measured. Furthermore the dust *within* the H II region *cannot* be absorbing (and consequently reradiating in the far-infrared) a significant fraction of the stellar ionizing radiation, i.e., the absorption optical depth at 900 Å cannot be much greater than 1. Thus, nearly all of the absorption observed in the visual and infrared must occur in a region exterior to the H II region; the bulk of the energy so absorbed presumably accounts for the far-infrared luminosity (cf. Wright 1973).

V. THE EXTINCTION TOWARD K3-50

Comparison of the available optical, infrared, and radio data yield estimates of the extinction toward K3-50. For the radio flux we have assumed that Higgs's (1970) deconvolution of the K3-50 complex is correct, $T_e = 10^4$ ° K, and that the (optically thin) 10-GHz flux is 7×10^{-26} W m^{-2} Hz^{-1}. This flux is uncertain, but is not likely to be in error by more than a factor of 2. We have chosen the 1.65-μ flux because it will contain a smaller contribution from dust emission than will the fluxes at longer wavelengths. In computing the values of C we have again used a reddening law given by the van de Hulst curve No. 15. In the infrared this reddening law obeys $\Delta \log F_\nu(1.65,\ 2.2,\ 3.5\ \mu) = (0.123,\ 0.075,\ 0.039) \times \Delta \log I(\text{H}\beta)$, respectively.[1]

The derived values of C are given in table 2, which shows that the extinction at Hβ appears systematically smaller when shorter-wavelength data are used. In interpreting this trend, it is important to bear in mind that the radio data summarized by Higgs (1970) show that the diameter of K3-50 is in the range 4″ to 7″. Thus, the object is bigger at radio frequencies than at optical frequencies. This size difference, however, cannot account for the large discrepancies between the different values of C. For example, if the Hα flux is corrected for extinction using $C = 3.8$, the resulting flux is too low by a factor of 50 compared with that expected from the radio data.

A further value of C can be estimated from the infrared data of Gillett *et al.* (1973). They have measured in K3-50 an absorption feature at 9.7 μ which is similar to the absorption they see in W3/IRS 5 and in the Becklin-Neugebauer object in Orion (Gillett and Forrest 1973). From the depth of this feature in K3-50, Gillett *et al.* (1973) estimate the visual absorption to be 40 mag, corresponding to a C of 18. The calibration of optical depth in the 9.7-μ features with visual absorption, however, rests on the identification of the Becklin-Neugebauer object as a highly reddened F supergiant. While this interpretation is probably incorrect (Becklin, Neugebauer, and Wynn-Williams 1973), the absorption at 9.7 μ *is* large and is probably indicative of a visual absorption considerably greater than is implied by the optical data.

VI. DISCUSSION

We will consider three ways of accounting for the discrepancies in the extinction. First, considerable approximately neutral extinction could be affecting the optical and near infrared fluxes. This is equivalent to a demand for a different reddening law toward K3-50. The net effect would be to superpose a relatively uniform amount of extinction throughout the visible and near-infrared onto a flux reddened by an amount indicated by the optical data. The discussion concerning the stellar luminosity argues against the neutral extinction model, because if the deficiency in the optical ionized-hydrogen emission compared with the radio is to be accounted for via neutral extinction, it would seem reasonable to require a corresponding increase in the 1-μ stellar flux. The resulting stellar luminosity is far greater than the measured infrared luminosity, which is presumed to be close to the bolometric luminosity of the source. We therefore consider this model unlikely.

Second, as has been recently suggested by Jones (1973), and Gillett *et al.* (1973), if a considerable fraction of the extinction at optical wavelengths is due to forward-scattering particles located in or near the emitting region, the optical emission will appear to be considerably bluer than expected from interstellar extinction. The differences in the values of C derived by comparing the optical, infrared, and radio data are thus in the sense one would expect from an optically thick forward-scattering sphere in which the albedo decreases with increasing wavelength. This model implies that the optical/radio deficiency is not real, but is a result of underestimating the optical reddening. If the scattering model obtains, the discussion of the stellar luminosity clearly becomes inoperative.

A purely scattering model can be argued against

[1] Another value of C could be derived from the [1.65 μ]−[2.2 μ] color if the emission at these wavelengths were due to reddened free-free emission alone. The 2.2-μ flux corrected for the extinction so derived is found to be far in excess of that extrapolated from 10 GHz. Thus there must be emission from dust even at 2.2 μ to account for the [1.65 μ]−[2.2 μ] color.

from size considerations. First, the consistency of the reddening of the stellar continuum and the nebular lines implies that the scattering must be affecting both approximately equally. The most simple model then consists of an H II region uniformly filled with scattering particles. The size of such an object, however, must be the same at radio and optical frequencies, contrary to observation. This difficulty can be circumvented by the introduction of peculiar distributions of gas and scattering dust, but the effectiveness of the scattering is significantly reduced in this case.

A stronger objection to a scattering model comes from a consideration of the stellar luminosity. Since the same apparent reddening ($C = 3.8$) applies both to the Hα flux and to the starlight, the factor of 50 deficiency in the corrected Hα flux compared with the radio flux must apply to the stellar flux at $\lambda 6563$ also. The resulting stellar luminosity is again greater than the measured infrared luminosity. This objection arises because reddening in a scattering model mimics neutral extinction.

Third, a geometrical model is suggested by the size difference at optical and radio frequencies. Such a model would consist of either one source of radiation with strongly spatially varying obscuration, or several sources with differing amounts of extinction. This model has analogies in the appearance of other galactic nebulae such as RCW 38 and RCW 57 (Persson and Frogel 1973; Frogel and Persson, in preparation) in which the radio and infrared sources lie in a dark region continguous with the optical source. The emission would be expected to shift slightly in position with wavelength, if, for example, the bulk of the gas responsible for the radio emission were completely obscured at optical wavelengths behind a very opaque cloud. The optical light would arise from the least-reddened emitting region, whereas the most heavily reddened region would dominate at radio frequencies. This is precisely the trend exhibited in table 2, namely the longer the wavelength, the more heavily reddened is the radiation.

Clearly the measurement of the stellar flux constrains a geometric model, since we are measuring most of the starlight at 1 μ, but less than 2 percent of the nebular flux at the same wavelength.

VII. SUMMARY AND CONCLUSIONS

The observations presented in this paper yield two important results: (1) The apparent reddening of the optical emission is relatively small. When the optically derived value of the extinction is applied to the observed line fluxes, radio and infrared fluxes are predicted which are considerably smaller than those actually observed. (2) The observed continuum at 1 μ is considerably in excess of that predicted for the atomic continuum from the observed values of the Hα and Paschen 7 fluxes. The presence of this excess continuum is independent of the reddening and is attributed to radiation from the exciting star or stars.

The inferred visual magnitude and spectral type of this star predicts a bolometric magnitude consistent with the measured far-infrared luminosity. The energetics of the source lead to the conclusion that most of the obscuration takes place outside the H II region, i.e., the dust emitting the far-infrared radiation does not compete effectively for primary ionizing photons.

A model that is consistent with the data requires variable extinction across the face of the source, with most of the region completely obscured optically.

The reddening toward NGC 6857, a nebula 1′ south of K3-50, is considerably less than that toward K3-50. This indicates either that NGC 6857 is considerably closer to us than K3-50 or that most of the extinction observed toward K3-50 occurs in its immediate vicinity. There is no evidence for a physical connection between the two objects.

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