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MAPS OF SPATIAL AND KINEMATIC STRUCTURE OF GALACTIC NEBULAE. I. H 76α STUDIES OF M17, M42, W51, AND DR 21

T. R. GULL
Kitt Peak National Observatory*

AND

B. BALICK
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz
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ABSTRACT

We have mapped M17 and M42 and observed W51 and DR 21 in the 76α transitions (2 cm) using the NRAO 140-foot (43-m) telescope. The spatial and velocity structure of M42 in this transition is very similar to structure observed in higher-α transitions. We find that a two-component velocity structure is present in M17. The two radial components are typically separated by ~ 17 km s^{-1} and are observable throughout a large portion of the radio nebula. W51 and DR 21 have H and He 76α lines similar to other recombination lines. C II was detected in all regions except DR 21.

Subject headings: nebulae — Orion Nebula — radio lines

I. INTRODUCTION

Recent kinematic studies of galactic H II regions at both radio and optical frequencies (e.g., Mezger and Ellis 1968; Smith and Weedman 1970; Meaburn 1971; Doherty, Higgs, and Macleod 1972; Bohuski 1973; Dopita *et al.* 1973; Balick, Gammon, and Doherty 1974*a*) have shown that spatial and kinematic structure of these nebulae is quite complex. Unfortunately, efforts to understand the structure have been hampered by apparent observational inconsistencies especially between radio and optical data. Radio observations have the advantage that they are unaffected by intervening dust and thus radio observations are sensitive to all of the emitting gas within the antenna pattern, whereas optical studies have the advantage of good spatial resolution and the availability of many emission lines arising from very different excitation conditions along the line of sight. Much can potentially be learned by a direct comparison of the optical and radio data, but such a comparison until recently has been difficult for a variety of instrumentally related reasons.

This paper is the first of a series in which coordinated radio and optical observations of the same spatial coverage and resolution are to be presented and compared. In this paper we concentrate on radio observations of recombination lines observed at 14.7 GHz (2 cm) using the 140-foot (46-m) telescope of the National Radio Astronomy Observatory.[1] In subsequent papers we report the results of optical studies with appropriate spectral and spatial resolution to allow a meaningful comparison of radio and optical results. We shall concentrate on the two brightest H II regions, M17 and M42, for which the spatial resolution (2′) is much smaller than the nebular size ($\geqslant 10'$). Other nebulae will also be studied as time permits.

II. OBSERVATIONS AND DATA REDUCTION

For the present observations the 140-foot telescope, a new dual-channel 2-cm receiver, and a 400-channel autocorrelation spectral-line receiver were used. The front end consists of two independent radiometers whose system temperatures were 130° and 200° K, respectively, while our observations were in progress. The autocorrelator was configured as two independent 192-channel spectral-line processors, and the output of each front-end channel was processed through its own line receiver. The cooler channel was centered on the H 76α line (laboratory frequency = 14,689.99 MHz) and the remaining channel on the He 76α line (14,695.97 MHz). Each system covered a 10-MHz bandpass (~ 200 km s^{-1}), and the frequency resolution was 63 kHz (1.3 km s^{-1}). The C 76α (14,697.32 MHz) emission line fell within the bandpass of the receiver used for He 76α observations.

Observations of M17 and M42 consisted of a grid of points with a spacing of $2' \times 2'$. This sampling interval was chosen to maximize coverage of the optically visible nebula in the available time, but does not provide a sufficient sampling density for the accurate construction of contour maps given our 2′ beam size (however, it turns out that most quantities of interest vary slowly enough so that contour maps can be reliably estimated). A reference point ($\Delta\alpha = 0$, $\Delta\delta = 0$) was chosen to coincide with the brightest continuum feature at 2 cm in each nebula. A number of 15-minute integrations were obtained at each point (using the "total-power" method); the total integration time was selected in an effort to provide a more or

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less uniform signal-to-noise ratio at each point. Every hour or so, a 5-minute observation was made at the reference point in order to check the instrumental performance and atmospheric extinction.

The observed positions are indicated in figures 1 and 2 (plates 1 and 2). Part *a* of each figure shows the grid of positions relative to the radio peak. Also shown are several brightness isophotes at 1.95 cm when observed with a 2′ HPBW beam (half-power beam width). These contours are taken from Schraml and Mezger (1969). The same coordinate grids and radio peak positions are superposed upon optical photographs in part *b* of figures 1 and 2. These are included to demonstrate the optical structure of the nebula, and to aid in referencing subsequent optical observations. The photographs were taken by one of us (T. G.) at prime focus of the Mayall telescope at Kitt Peak National Observatory. Both photographs were recorded using interference filters with 90 Å bandpass (full width at half-intensity). The photograph of M17 is of Hα and [N II] emission and the photograph of M42 is of [S II] (6717 and 6731 Å) emission. Other plates of these fields will be published subsequently.

The scans at each point were weighted by the ratio of (signal to noise)/(normalized atmospheric extinction)^2 and then averaged. The signal-to-noise ratio was essentially constant for all scans, and the normalized atmospheric extinction varied only slowly but repeatedly with local hour angle, from unity at the meridian up to a factor of 2 near the horizon. A third degree ($n = 3$) polynomial was fit to the baseline adjacent to the line and then subtracted. This large value of n was necessary to represent adequately the sinusoidally varying baseline undulations caused by standing waves in the dish structure. The final results are not sensitive to the selection of n for $n = 2$ or 3, except for perhaps the widths of the weakest wide (>20 channels) lines. The spectra were then smoothed by three channels to yield a velocity resolution of ~ 4 km s^{-1} and a signal-to-noise ratio of $\gtrsim 70$ for the hydrogen lines ($\gtrsim 5$ for the helium lines).

Single Gaussian profiles were fitted to the hydrogen and helium lines for each point observed in M17, M42, W51, and DR 21. The line height, center, and width were treated as free parameters, although the center and width could have been fixed as desired. Except in M17, which is discussed separately below, the convergence was rapid and the residuals were flat. In general, we felt the blended helium/carbon spectra were too noisy to permit a detailed quantitative analysis. We shall discuss the He/C results only in a few cases where the signal-to-noise ratio is adequate. Nonetheless, it is safe to state that the available helium data showed no significant anomalies when compared to the hydrogen profiles at each point.

Errors are not normally given with the data presented below. The line-fitting algorithm gives error estimates which we felt to be unrealistically small. In general, line heights have 1 σ errors given by the root mean square (rms) deviations of the residuals. Line-velocity errors are probably less than 0.5 km s^{-1} (1 σ). Line-width errors are rather sensitive to the signal-to-noise ratio. Most widths are good to within 2 km s^{-1} (1 σ) unless otherwise indicated.

III. RESULTS

M17.—M17 is one of the brightest optical nebulae in the summer night sky. In spite of this, the nebula has not been as extensively studied at radio frequencies as has the well-known winter nebula, the Orion Nebula (M42), probably because of the proximity of many other interesting nebulae. This is indeed unfortunate, for in many respects M17 is one of the most interesting, yet at the same time enigmatic, of the bright H II regions.

The source was observed at 21 points most of which are situated in regions of bright optical nebulosity (fig. 1). Other points, particularly in the far west and south, appear in regions of rather strong obscuration. Thus, M17 and M42 are similar in that portions of each nebula are heavily obscured behind what is presumably local dust. Also similar to M42, there are strong infrared extended and point sources in obscured regions (Kleinmann 1971; Lemke and Low 1972; Harper 1974). Some molecular emission, such as H_2O and CO, has been observed in M17 (Lada, Dickinson, and Penfield, to be published, and references therein).

The most striking feature of the M17 recombination line is its shape. Although the typical line profile is symmetric (fig. 3*a*), fitting and removing a single Gaussian component shows that the line is clearly non-Gaussian since systematic variations appear in the residuals (fig. 3*b*). This same behavior has been reported previously by Cesarsky (1971) whose results are discussed below. Such a line shape must not be deemed anomalous for in all H II regions, except perhaps Orion A, the radio recombination lines are not well fitted by a single component.

A similar line shape is seen at most points in M17. In an attempt to analyze the changes implied by the slowly varying line shapes, we have tried a multi-component Gaussian decomposition of the observed lines. In our analysis, two Gaussian components were fitted simultaneously. The justification for this approach is not only that it is successful (i.e., a set of line parameters can always be found which remove all systematic variations from the residuals), but in addition, profiles of several optical lines observed at one point in M17 with high spectral resolution show the presence of two major components (these profiles were kindly supplied by Barry Lasker and Malcolm Smith). However, it is certainly possible that an analysis based on two Gaussian components may be a gross over-simplification.

Fitting two Gaussian lines involves the determination of up to six parameters; i.e., the line heights, centers, and widths. In our analysis we found that, because of noise in the data, it is possible to fit the line adequately with fewer than six free parameters with little degradation of the rms deviations of the residual. To be specific, if we assumed both lines to have the intrinsic widths much like those seen in other H II

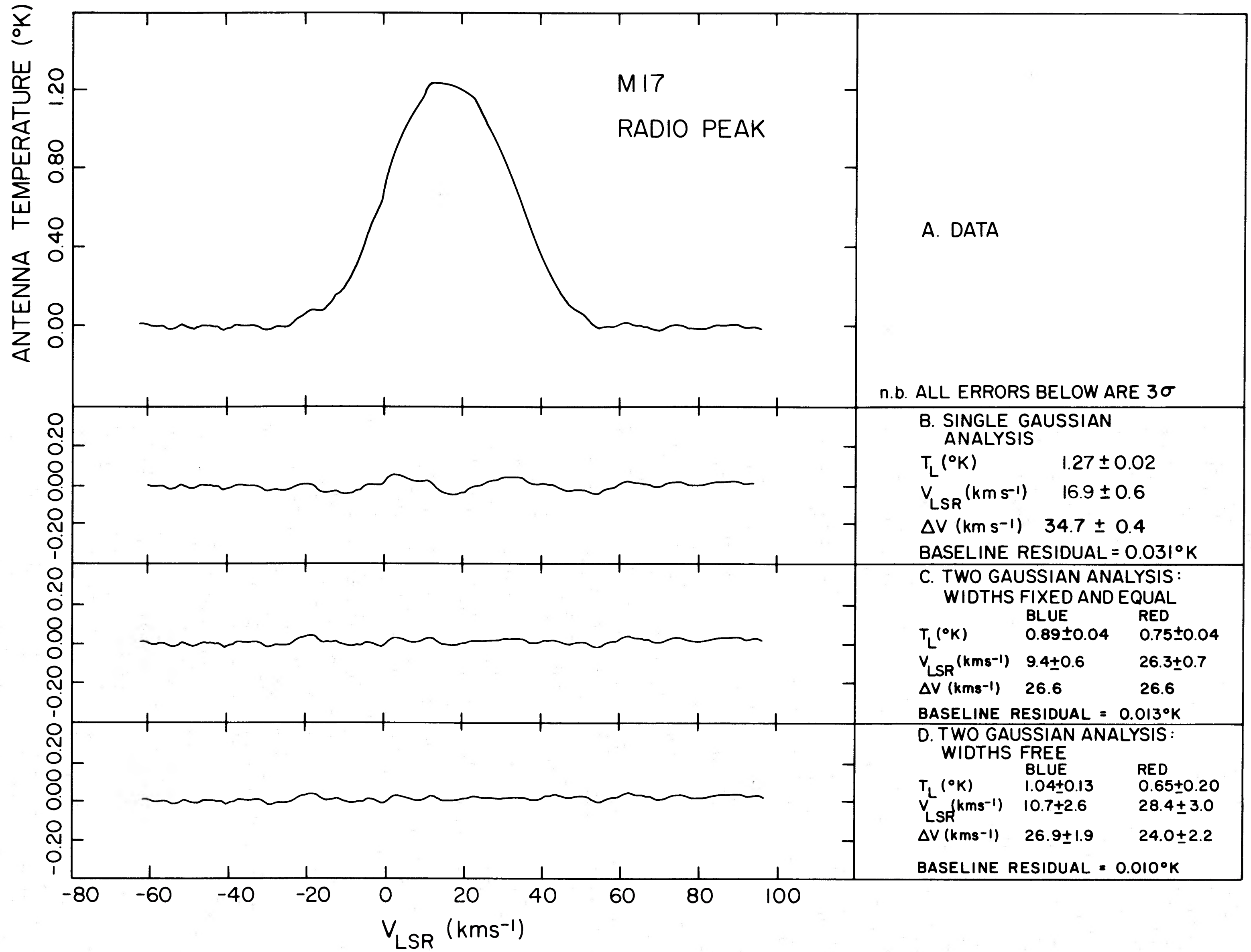

FIG. 3.—H 76α transition profile recorded at the radio peak of M17 and examples of the results and residuals after three different Gaussian analyses were applied to the data.

regions, we still obtain a good solution in which all systematic variations in the residuals are removed. The results of such a four-parameter fit are shown in figure 3*c* and, for comparison, a six-parameter fit is illustrated in figure 3*d*. (Note that the differences in the residuals and the associated standard deviations are small.) In the discussion which follows, we have chosen to use a four-parameter analysis in which the widths are fixed at equal values. We adopted this approach because it obeys the principle of Occam's razor (i.e., it is the simplest, most straightforward approach which is successful), and also it enables us to avoid some solutions which are nonconvergent, physically impossible, or grossly inconsistent with results obtained at adjacent points.

The choice of the proper widths for each of the lines is not obvious. We were guided by an extensive point-by-point analysis of the data in which a range of widths from ~ 20 to $36\ \mathrm{km\ s^{-1}}$ were assumed. We found that the rms deviations of the residual tended toward a well-defined minimum for widths between 24 and $30\ \mathrm{km\ s^{-1}}$ at most points; consequently, a width of $27\ \mathrm{km\ s^{-1}}$ was chosen for both lines. Line widths of the other H II regions studied (M42, W51, and DR 21) as well as the widths of many other H II regions strongly support this choice. Nonetheless, it must be emphasized that a width of $27\ \mathrm{km\ s^{-1}}$ is chosen more to minimize the rms deviations than for any other reason.

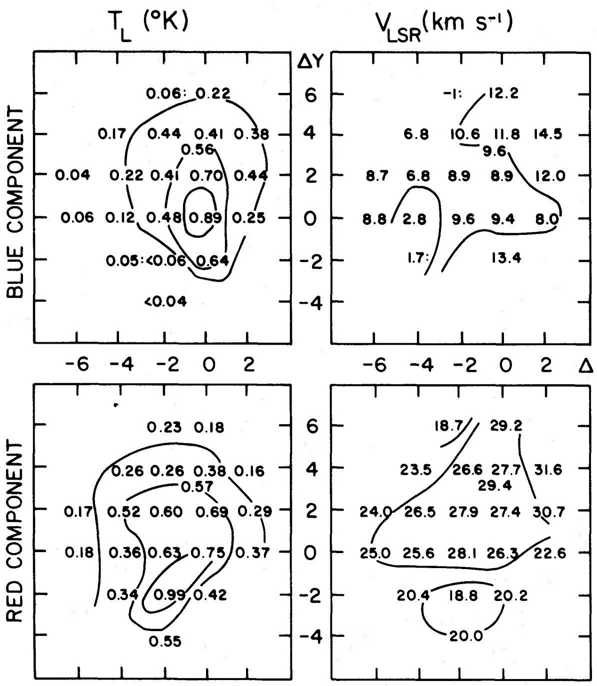

FIG. 4.—Line temperatures (T_L) and velocities (V_{LSR}) for the red and blue velocity components of M17. The lines represent estimated contours. The contour spacing is every 0.25° K for T_L and every $5\ \mathrm{km\ s^{-1}}$ for V_{LSR}. ΔX and ΔY are beam offsets from the radio continuum peak at 1.95 cm (0, 0) in arc minutes; $\Delta\alpha = -\Delta X/\cos\delta$ and $\Delta\delta = \Delta Y$. The line widths are fixed at $27\ \mathrm{km\ s^{-1}}$.

The results of this analysis are shown in figure 4. We use the conventional "red" and "blue" to describe the Gaussian line fits at greater and lesser velocities, respectively. It can be seen that the line temperatures and velocities (relative to the LSR) vary regularly from point to point. We should remark that in some of the outermost portions of the nebula, the spectral lines become quite narrow and sometimes asymmetrical, implying that one of the components decreases in relative intensity.

The line emission from the blue component appears peaked and centered near the continuum peak, whereas the distribution of the red component is larger in scale. Velocity gradients appear to be present for both components; these gradients are larger in magnitude (1–$2\ \mathrm{km\ s^{-1}\ arc\ min^{-1}}$) than seen in M42. The velocity difference between components ranges between about 10 and $20\ \mathrm{km\ s^{-1}}$ with an average value of $\sim 17\ \mathrm{km\ s^{-1}}$. The spatial distribution of line intensity and velocity show some correspondence with optical features. In particular, the blue component appears coincident with the heavy obscuration to the west of the optical nebula and where the brightest radio emission is found. The red component extends into the northeast toward the region of brightest Hα emission. There is no evidence of spherical symmetry in the spatial and kinematic features seen in these H 76α observations.

The helium- and carbon-line results are more difficult to analyze than the hydrogen because of their poorer signal-to-noise ratio. A single Gaussian component analysis of the helium line has been made, and shows results consistent with a similar analysis of the hydrogen lines. Where the hydrogen line widths are widest ($\sim 36\ \mathrm{km\ s^{-1}}$ because of splittings), the helium lines show half-power widths in agreement to within 10 percent; further, where the hydrogen lines tend toward smaller widths ($\sim 26\ \mathrm{km\ s^{-1}}$), the helium lines become even narrower ($\sim 18\ \mathrm{km\ s^{-1}}$). These trends in the widths reflect the changing relative importance of thermal and velocity broadening effects. In addition, there is no evidence of different H II and He II emitting volumes, unlike in M42.

Carbon lines appear at a level of about 3 times the rms noise in several positions in M17, all in regions of obscuration to the west and south. The ratio of carbon-to-hydrogen emission, relative to its value at the nebular peak, rises by about half an order of magnitude in the west, and by as much as one order of magnitude in the south. This correspondence between C II emission and nebular obscuration is not surprising, for it is known that C II emission arises in neutral regions adjacent to the H II/H I interface at these radio frequencies (Zuckerman and Ball 1974; Balick *et al.* 1974*a*). The carbon line widths are difficult to estimate, but appear to be small at each point ($4 \pm 2\ \mathrm{km\ s^{-1}}$). A spectrum formed from a composite of the point-by-point spectra shows the carbon line clearly at a velocity of $18\ \mathrm{km\ s^{-1}}$ (fig. 5). This velocity is intermediate between the average velocities of the red and blue H 76α components. The width of the composite line is $6\ \mathrm{km\ s^{-1}}$, but this result may be an

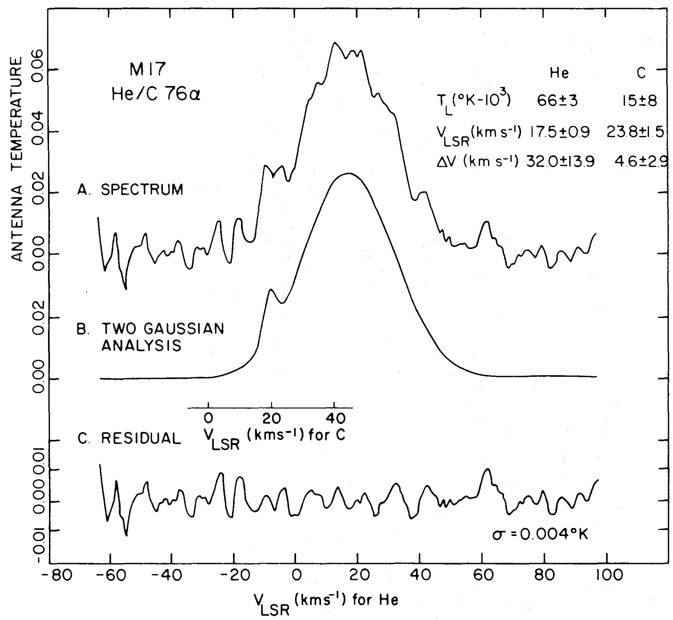

FIG. 5.—The 76α profile of He II and C II in M17. The spectrum is a composite of all He II–C II spectra recorded in this experiment. The best line-fit parameters and residuals are shown.

overestimate because of velocity gradients in the C II emitting region. We would like to remark that no observations were made in the obscured regions to the north and east where a strong 100-μ infrared source has recently been discovered (Harper, 1974).

M42.—The Orion Nebula (M42) was observed at 13 points on a 2′ × 2′ grid (fig. 2), much like M17. The primary motivation for the present observations was to provide a systematic set of measurements for comparison to optical data to be obtained later. Because this nebula has been surveyed by others at similar radio frequencies and spatial resolutions (e.g., Doherty *et al.* 1972; Balick *et al.* 1974*a*, and references cited therein), and because the present data show no substantial differences with previous results, we shall not discuss these observations in detail at this time. Any differences are small and can be accounted for by differences in primary beam sizes and the known velocity gradient.

The spectra were found to be well fitted by single Gaussians at each point. The distribution of the H 76α line temperature, velocities, and widths are shown in figure 6. The velocity pattern and distribution of widths are similar to results already published, although we find that the velocity gradient tends to increase at the nebular boundaries.

The available helium and carbon data are consistent with measurements obtained with a better signal-to-noise ratio reported by Chaisson (1973) and Balick *et al.* (1974*a*). In addition, there appears to be a small but systematic velocity difference between the hydrogen and helium lines of ~1.5 km s^{-1} (which is corroborated by Balick *et al.* 1974*a*). This, and the decreasing helium-to-hydrogen intensity ratio beyond 2′ from the peak seem to suggest that the He II region is interior

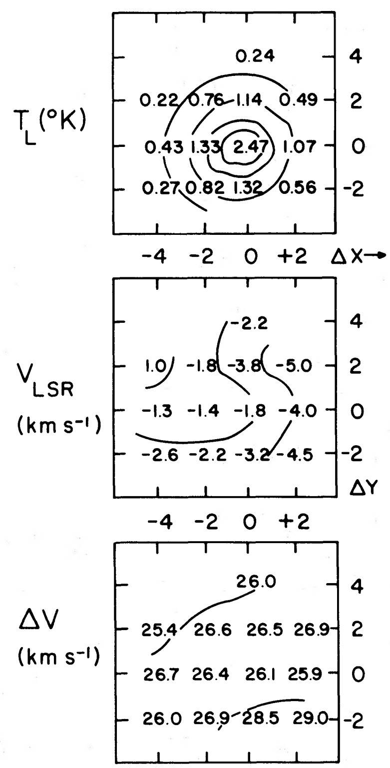

FIG. 6.—Line temperatures (T_L), velocities (V_{LSR}), and widths (ΔV) for M42. The lines represent estimated contours. The contour spacing is every 0.5° K for T_L and every 2 km s^{-1} for V_{LSR} and ΔV. ΔX and ΔY are beam offsets from the 1.95-cm radio peak (0, 0) in arc minutes; $\Delta\alpha = -\Delta X/\cos\delta$ and $\Delta\delta = \Delta Y$.

TABLE 1

RESULTS FOR W51 AND DR 21

Source	T_L (° K)	V_{LSR} (km s^{-1})	ΔV (km s^{-1})	rms (° K)
		H 76α		
W51 (G49.5−0.4)	1.00	+57.5	29.9	0.008
W51 (G49.3−0.3)	0.19	+54.6	30.4	0.01
DR 21	0.30	− 1.2	34.3	0.007
		He 76α		
W51 (G49.5−0.4)	0.12	+57.2	27.2	0.01
W51 (G49.3−0.3)	0.02	+58.7	$\lesssim$40	0.008
DR 21	0.02	− 1.3	~25	0.008

to the H II region, as first suggested by Leibowitz (1973). We also find the C II distribution to be larger in scale than that of the H II distribution. The ratio of carbon to hydrogen emission, relative to its value at the peak, increases outward from the peak, especially toward the dark bay region. This is in accord with data at 3 cm (Balick *et al*, 1974*a*).

W51 and DR 21.—The sources W51 and DR 21 were observed as time permitted. Two continuum sources in the northern "A" complex of W51, G49.5−0.4 and G49.3−0.3, were studied. The signal-to-noise ratio in these observations tends to be better than in M17 and M42 since longer integration times per point were possible. The results of the H and He 76α line analyses are shown in table 1. Also shown is the rms of the residual. The uncertainty (1 σ) in the line widths of the weak helium lines is probably ~5 km s^{-1}. The values shown for the hydrogen line are generally consistent with results of Mezger *et al.* (1967), Terzian and Balick (1969, 1972), Reifenstein *et al.* (1970), and Wilson *et al.* (1970) with some minor exceptions concerning the velocity of G49.3−0.3 and the widths of G49.3−0.3 and DR 21. For DR 21, a trend may exist towards larger line widths from 15 to 5 GHz (2 to 6 cm); however, further observations are required to establish this possibility. If real, such a trend may indicate the presence of Stark broadening. Also, the present observations represent the first positive detection of He recombination lines in DR 21; we find an abundance of He^+ about 5 percent that of H^+.

No evidence of carbon in DR 21 was found. However, in W51 a nearly unresolved carbon feature ($T_L \simeq 0.03°$ K) appears at both positions at a velocity of 68 km s^{-1}. This feature stands out clearly in G49.3−0.3 but is more difficult to isolate in G49.5−0.4 because of the stronger helium line on which the carbon is superposed. W51, then, is yet another example in which the carbon distribution is much different from, and probably larger in scale size than, the H II distribution.

IV. DISCUSSION

We now compare the results for M17 presented in § III with previous observations. Cesarsky (1971) and Chaisson and Lada (1973) have observed the radio recombination line emission at several frequencies. Cesarsky's one Gaussian analysis at 3 and 6 cm shows much the same systematically varying residuals as do the present observations. At 18 cm, the H 157α line reported by Cesarsky appears 10 percent broader and is well fitted by one Gaussian line. In order to understand the H 157α observation taken with a beam of half-power width (HPW) ~18′, we have averaged together all of our scans (simulating a beam whose HPW is larger than the 10′ size of the radio nebula). We find the average profile to be well fitted by one Gaussian component whose width $\Delta V = 41 \pm 2$ km s^{-1} and velocity = 18 ± 1 km s^{-1}. These values compare well with the H 157α measurements of $\Delta V = 39 \pm 1$ km s^{-1} and $V = 17 \pm 2$ km s^{-1}. Therefore spatial averaging of complex mass motions is the most probable explanation of Cesarsky's H 157α line measurements.

The carbon line has been observed previously in M17 by Churchwell (1970) (3 and 6 cm), Cesarsky (1971) (18 cm), Menon (1970) (21 cm), and Simpson (1970) (21 cm). The present results resemble the 3 cm results and tend to disagree in velocity by ~6 km s^{-1} with the lower frequency observations. A partial explanation for this behavior may be afforded by beam size and spatial broadening effects; however, the systemic changes in the C II velocity with frequency make it likely that two different carbon-emitting volumes dominate the C II emission at high and low frequencies. This has been previously suggested by Balick *et al.* (1974*a*) and Zuckerman and Ball (1974) for M42 and by Parrish, Pankonin, and Terzian (1973) for W49.

Optical observations of lines formed in the ionized region of M17 give fascinating results. Meaburn (1971) has obtained profiles in some regions of the nebula which show the line shape to be quite complex; however, his velocity resolution (~10 km s^{-1}) was about equal to the velocity difference between lines. High-velocity resolution studies of He 10,830 Å (Gull 1971) and of Hα, [N II] 6584 Å, [O III] 5007 Å, [S II] 6717 Å, 6731 Å, and He I 5876 Å (Smith and Lasker 1973) show the profile to be complex. Their [N II] line profiles clearly show line splitting in at least one position with components whose velocity difference is in excellent agreement with the present results. Interestingly, lines of lower excitation, [N II] and [S II], show much different red and blue component intensity ratios than do the higher excitation, [O III], or Hα lines at the same position. Clearly there are large differences of excitation along at least this one line of sight.

In order to gain insight to the spatial and kinematic structure of M17, it is useful to refer to models proposed for M42. Such models have been suggested often in the past (see reviews by Terzian and Balick 1974; Zuckerman 1973; Balick *et al.* 1974*a*). An empirical model in which there exists a dominant primary flow of ionized gas from a background neutral complex directed along the line of sight (as well as secondary flows from other neutral regions) can explain the multifarious observations of M42 (Balick, Gammon, and Hjellming, to be published). The strongest flows originate from the densest neutral gas near the major source of ultraviolet excitation, θ^1 C. The present data are certainly consistent with the proposed model, and suggest that a corresponding model might be developed for M17.

In M17, however, the situation is somewhat more complex. No star has been unambiguously identified as the exciting star, although several candidates have been suggested (Schulte 1956; Herbig 1973). Furthermore, the spatial and dynamic structure in M17 is far more complicated than it is in M42. It appears, however, that flows from a background and foreground neutral complex affect the H 76α emission in most parts of the nebula. This neutral complex is also responsible for the deep obscuration in the south and west, and its interface with the H II region produces the C II emission observed in the same regions. This suggests the neutral complex may be "bowl" shaped with the bowl bottom in the southwest, and sides in the foreground and background. The actual configuration is probably somewhat more complex, as indicated by the radio continuum observations of Schraml and Mezger (1969) and Webster, Altenhoff, and Wink (1971).

V. CONCLUSIONS

In this paper we have presented maps of the H 76α line parameters in the bright optical and radio H II regions, M42 (Orion A) and M17. We also observed W51 components G49.5−0.4 and G49.3−0.3 and DR 21. The principal results are as follows:

1. In M17, two radial velocity components, separated in velocity by ~20 km s^{-1}, are observed throughout a large portion of the radio nebula.
2. C II emission in M17 has been detected in the vicinity of the nebular boundaries in regions of heavy obscuration. The C II velocity lies between the velocities of the H II velocity components.
3. Orion A exhibits spatial and kinematic properties at 2 cm consistent with previous observations at longer wavelengths.
4. Likewise, the H 76α and He 76α lines seen in DR 21 and W51 are similar to other previously observed recombination lines. C 76α emission was clearly detected in W51 but not in DR 21.
5. Morphologically, M17 seems similar in many respects to Orion A. However, the nebular kinematic structure of M17 appears somewhat more complex than in Orion A, and an empirical model to explain the structure of M17 must be deferred until further observational information is available.

We feel that detailed optical and radio observations would help clarify the structure of M17. Yet to be reported, for example, is information regarding the exciting stars and maps of the extinction and ionization structure. Future papers will address themselves to some of these problems.

We most gratefully acknowledge helpful discussions with Dr. Malcolm Smith, and we wish to thank him and Dr. Barry Lasker for supplying unpublished optical line profiles of M17. We also wish to thank the staff of the NRAO for their assistance in obtaining and reducing the data, and the staff of the KPNO for their assistance with the 4-meter telescope observations and manuscript preparation. One of us (B. B.) was a research associate at the NRAO while the radio observations were obtained.

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Dr. Bruce Balick
Lick Observatory, Santa Cruz, CA 95064

Dr. T. R. Gull
Kitt Peak National Observatory, P.O. Box 26732, Tucson, AZ 85726

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RAPID LINE VARIABILITY. I. Ap STARS EPSILON URSAE MAJORIS AND 73 DRACONIS

Michel Breger*
University of Texas at Austin and McDonald Observatory
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ABSTRACT

Because of various reports in the literature about rapid variations of hydrogen and calcium lines in these two Ap stars, about 500 photoelectric hydrogen and calcium profiles have been obtained with high time resolution. No line-profile or equivalent-width variations beyond the expected errors could be found. In fact, for ϵ UMA, a very bright star, the Hα equivalent widths were constant to 0.2 percent during the time of observation.

Subject headings: line profiles — peculiar A stars — stars, individual

I. VARIABILITY OF PECULIAR A STARS

Light and spectrum variability is common among the peculiar A stars of the SiSrCrEu group. This variability is quite complex and can provide considerable insight in the unusual physical processes taking place in the Ap stars. The reported variability can be divided into three, possibly physically different, types of variability:

i) The main continuum and spectral-line variation shows a period equal to the rotation period of the star (see Preston 1971 for more details). The origin of this variability lies in the abundance spottiness of the stellar surface and the far-ultraviolet absorption of radiation by overabundant metals (Molnar 1973). The optical-light variability is usually less than 0.1 mag and periods usually are several days.

ii) Short-period continuum variations with time scales of 30 minutes to 2 hours may be superposed on the long-period variation. Such amplitudes are generally close to the limits of detectability (~0.01 mag or less) and the significance of the reported variations may be difficult to determine. On the other hand, the reported variations cannot be immediately dismissed (e.g., Rakos 1966; Maitzen and Moffat 1972; Stępień and Romaniuk 1973). The 2-hour periods are close to those expected if pulsation occurs in Ap stars (Breger 1969), but would require pulsation in the first or second overtone. However, our (unpublished) *Q*-value analysis for the δ Scuti variables show that the δ Scuti stars hotter than $T_{\text{eff}} = 7800°$ K also pulsate in the first or second overtone, and the observed *Q*-values for the (even hotter) Ap stars become even more interesting. One problem star remains, 21 Com. The reported half-hour period (Bahner and Mawridis 1957) is too short for pulsation in the "reasonable" overtone. In order to test for the reality of the reported period, we have reobserved this star during 1969 on the 24-inch (61-cm) reflector at Lick Observatory. Indeed, a 32-minute period was also found, but the significance of the 0.007 mag amplitude was only 2 σ above noise and the project was abandoned. This probably was a mistake. The beautiful observations by Percy (1973) confirm the short period. The relatively large amplitude up to 0.02 mag, present at the time of observation, seems to establish firmly the reality of the half-hour period of 21 Com. These short variations may also be expected to show up as radial velocity variations, especially if pulsation is involved. In this regard it is unfortunate that the extensive survey by Abt and Snowden (1973) was inconclusive.

iii) Very rapid changes on the order of minutes in the shape and equivalent widths of hydrogen and calcium lines have also been reported. For ϵ UMa Wood (1964) reported a 12 percent change in the Hβ strength in a 4-minute interval. The variations seemed to be confined to the hydrogen wings about 15 Å from line center. 73 Dra has also been reported to have hydrogen- and calcium-line variations on the time-scales of several minutes to 1 hour (Wood 1964; Honeycutt 1966; Bonsack and Markowitz 1967). Older references can be found in the Wood papers. These results would require that successive members of the Balmer series sometimes vary out of phase with each other, while at other times the hydrogen-line variations appear to be in phase. Any variation of the hydrogen lines out of phase is physically quite puzzling. Similar variations were also proposed for HR 9080 (Wood 1968), HD 51418 (Gulliver and Winzer 1973) and HD 215441 (Wood 1967). The latter star appeared to show a change greater than 30 percent in the Hβ equivalent width in 90 seconds! However, some "normal" stars also have been claimed to be variable: β Car (Al IV) has been reported to show oscillations in the *core* of Hβ with a quasi-period of 35 minutes (Wood and Hollis 1971).

In our view, the reality of many of these previous line-variation results can be challenged on the basis that a full analysis of observational errors and a clear difference between nonvariable comparison stars and variable Ap stars has not been established. However, the size of the reported variations is very intriguing and considerably more observations with photoelectric rapid scanning techniques seem indicated. We have started such a program and the present paper reports

* Visiting Astronomer, Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

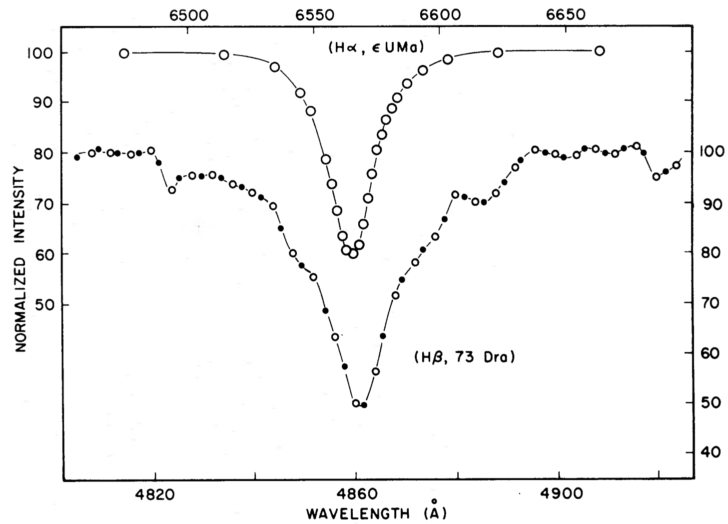

FIG. 1.—Average line profiles observed for rapid variability. In the Hβ profile the open circles represent observations made on 1972 August 17, while the filled circles were observed on 1972 August 20.

our results for the two most promising Ap stars: ε UMa and 73 Dra.

II. NEW RESULTS

Two rapid spectrum scanners were used on five nights to look for rapid line variability in the two Ap stars 73 Dra and ε UMa. A bright supergiant, α Cyg, was also observed for comparison. The ε UMa observations were obtained with the HCO scanner attached to the 92-cm telescope of the Kitt Peak National Observatory (KPNO). All other measurements were made with the Tull scanner attached to the McDonald Observatory 2-m telescope. Bandpasses of 4 Å were selected. Each individual observation consists of a large number of rapid scans across the profile of the selected line. Every 45 s (KPNO) or 3 minutes (McDonald Observatory) the accumulated data in the 30 or so channels were stored on tape. Since some of the previously reported variability had occurred in the near wings of the hydrogen lines, we took great care to include the wings in our observations. This is demonstrated in figure 1, where two of the mean profiles are shown. Observational errors should be negligible in these mean profiles. The marked departure from a smooth "theoretical" Hβ profile shown by 73 Dra is caused by the presence of metallic lines.

The following reduction procedure was adopted: since we were not interested in any night-to-night variations (which are likely to exist due to the rotation of the spotted surface), data from different nights were not combined. For each set of observations an average line profile was computed. We then searched the individual observations for intensity variations at all wavelengths relative to the mean profile. This technique should pinpoint any variations in all or part of the wings, wall, and line core. Our analysis cannot detect any broad-band changes which affect all parts of the profile in the *same* way. However, since the previously reported variability showed changes in the profile shape, this is not deemed a deficiency. We then calculated equivalent widths by defining several wavelengths in the far wings of the lines to be continuum and calculating the widths in the standard manner. All the equivalent widths were normalized by setting the average width for each set of observations equal to 1.0.

These observed variations then need to be compared with the expected errors. One potentially large source of error is photon statistics. For a typical count of 20,000 counts per channel one would expect a photon-statistics error per channel of just under 1 percent. For the equivalent widths (EW) photon statistics are also not negligible. One obtains a large absolute uncertainty from the continuum and wing channels because the flux is large there and the statistical uncertainty therefore is also large. (The *relative* uncertainty is immaterial here.) Hence one has the situation where the line core contributes most of the EW, while the wings and continuum contribute most of the uncertainty of EW. In the present work, the statistical uncertainties due to continuum and line are comparable. This is true despite the fact that the continuum values were interpolated from approximately four continuum channels on both sides of the line, with the corresponding reduction of the continuum uncertainty by another factor of better than 2.

Another source of error concerns the small drift of the image in the entrance diaphragm and the corresponding shift in wavelength of the profile. For high-precision photoelectric scanning a slit to reduce this problem cannot be used. Despite careful guiding we obtained a "wandering" of the profile of about 1 Å. This is translated into an equivalent width error only when the profile is not absolutely smooth but contains many lines. The wavelengths selected to represent the continuum were as free from lines as was practical. The effect of the "wandering" is to decrease the resolution during an integration, and, in general, to

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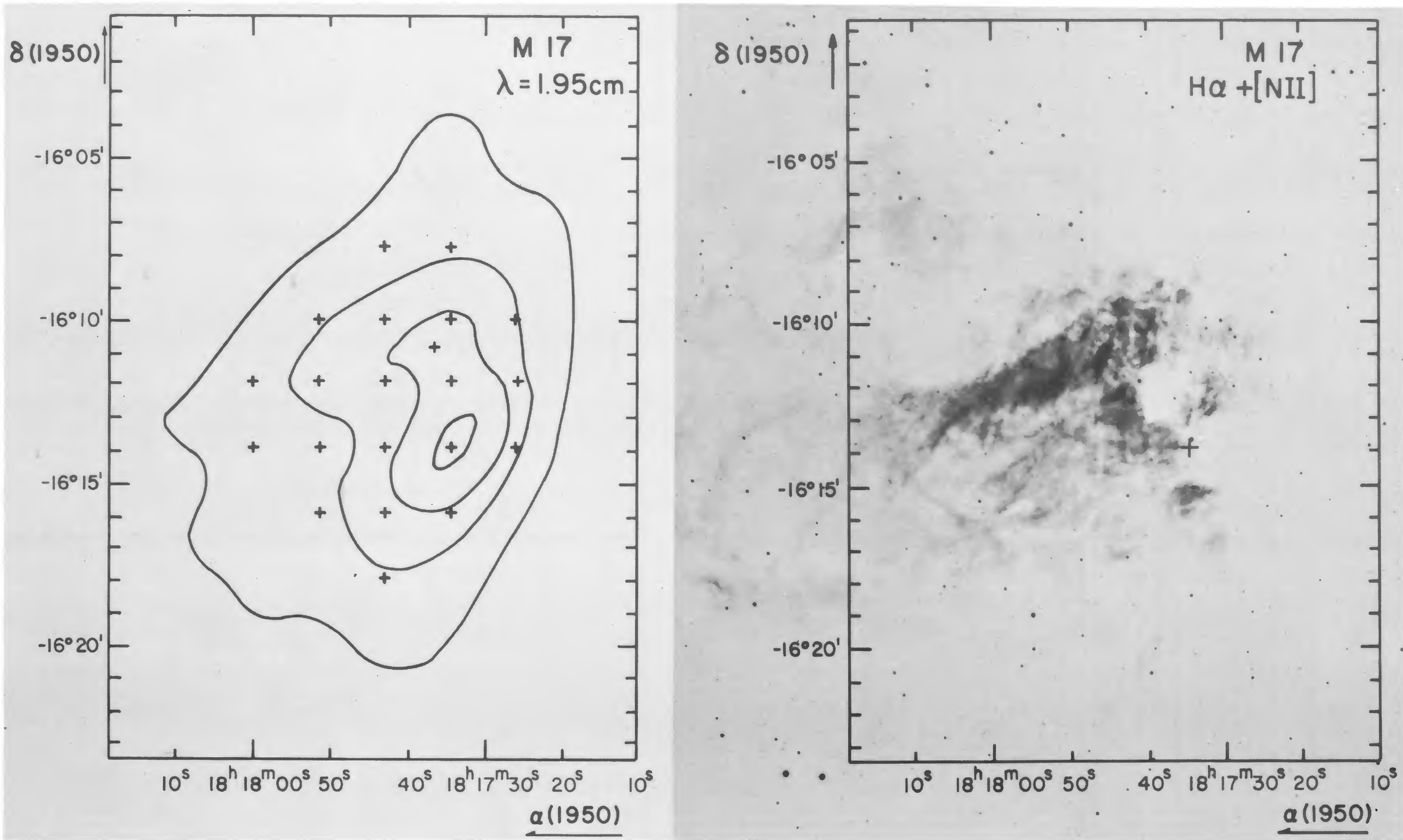

FIG. 1.—*M17*. The optical photograph was taken at the prime focus of the KPNO 4-m telescope using an interference filter passing Hα and [N II] 6548 Å + 6584 Å. At the same scale, some radio contours of 1.95-cm continuum radiation (Schraml and Mezger 1969) are shown. Crosses indicate the observed positions in this study. The reference position is indicated by a cross on the optical photograph.

GULL AND BALICK (*see* page 64)

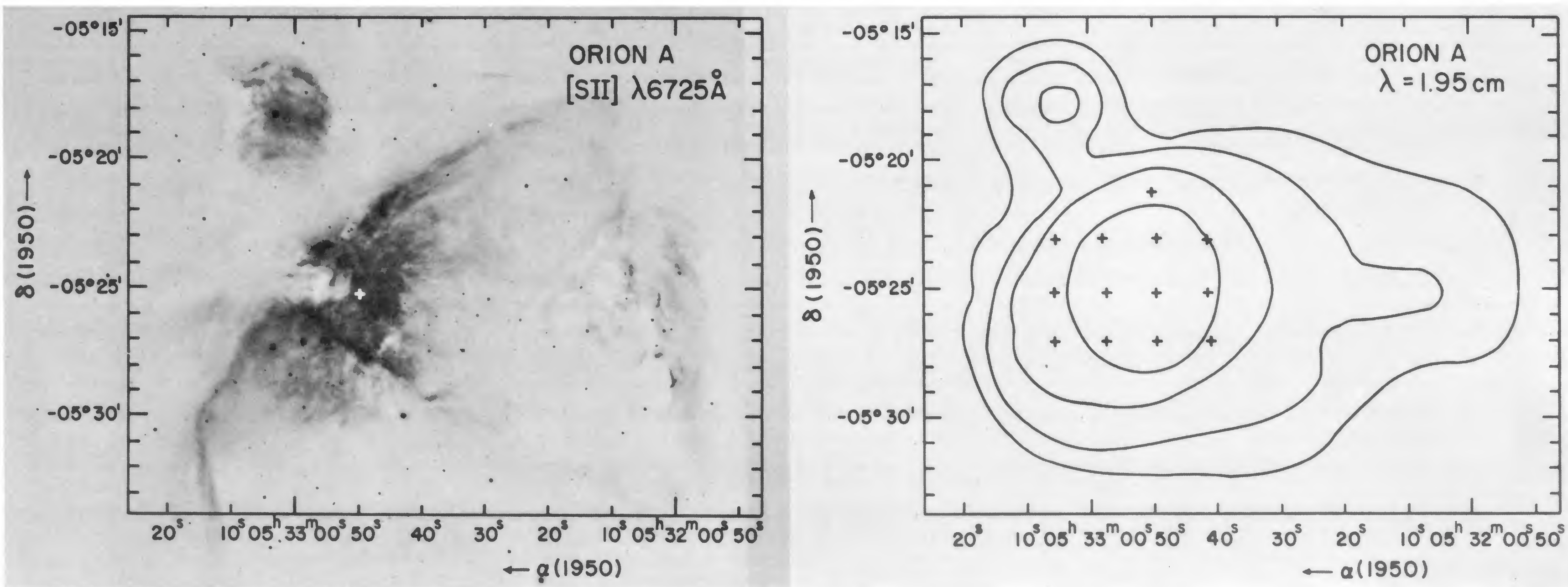

FIG. 2.—*M42*. The optical photograph was taken at the prime focus of the KPNO 4-m telescope using an interference filter passing [S III] 6717Å + 6731 Å. See also the legend for fig. 1.

GULL AND BALICK (*see* page 64)