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THE DUST AND GAS SURROUNDING LkHα 101

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ABSTRACT

The linear polarization of the reflection nebula NGC 1579 and the CO (1 → 0) emission from the associated molecular gas have been mapped for several minutes of arc around the exciting star LkHα 101. These maps show conclusively that LkHα 101 is the sole significant source of illumination in the region. The dust in the reflection nebula appears to be uniform over the illuminated region and is uniformly illuminated by LkHα 101. Despite the patchy obscuration, the dark cloud which obscures LkHα 101 does not surround the star. LkHα 101 may have formed out of a placental cloud whose remnants now include four molecular cloud fragments, two in front of and two behind the reflection nebula, as well as an H I cloud previously detected in the region.

Subject headings: nebulae: individual — nebulae: reflection — polarization — stars: emission-line

I. INTRODUCTION

LkHα 101 ($\alpha = 04^h26^m57^s.3$, $\delta = 35°09'56''$ [1950]) is a solitary B star hidden behind a dust lane. It is coincident with the H II region S222 and lies at the center of the reflection nebula NGC 1579. Because it is not a member of a cluster, it is a good example of a single, hot, young star dispersing its placental cloud without the interference of previous generations of stars. Even this is a complex process, and the region has been studied for many years because of its peculiar properties.

This paper presents a close examination of the clouds immediately surrounding the star. It will be shown from optical polarization data that LkHα 101 is the sole significant source of illumination for the reflection nebula and that the dust responsible for the reflection nebula is not directly related to the foreground dust cloud which obscures LkHα 101. Also, by mapping the CO (1 → 0) line, it will be shown that the molecular gas is clumped into several small clouds both in front of and behind the reflection nebula. Simple arguments will show that these clouds must have existed as density clumps in the molecular cloud before LkHα 101 ignited.

Before proceeding further, it is important to establish some nomenclature for the region. Referring to Figure 1, LkHα 101 is the name of the central star. S222 will refer to the H II region surrounding the star. Although S222 is best studied in the radio, it enters this study as a region of Hα emission seen most intensely just to the north of the stellar image. NGC 1579 will refer to the reflection nebula. The exact relationship between S222 and NGC 1579 is somewhat problematical and will be discussed below. The band of heavy obscuration running across the reflection nebula from the eastern side, in front of LkHα 101 and down to the south will be referred to as the obscuring cloud and will be a primary object of this study. The small triangular patch of obscuration to the north of the star will be referred to as the northern cloud. In addition, there are two further patches of molecular emission, which will be referred to as the southern cloud and the southwestern cloud, which do not correspond to any features in Figure 1 and must lie beyond the reflection nebula.

Very little is known about LkHα 101 as a star. Nothing observed in the optical spectrum relates directly to the star. There are many emission lines (Herbig 1971), which presumably arise in circumstellar gas. The H and K lines are very strong in absorption, which initially misled Herbig (1956) into classifying LkHα 101 as an F dwarf. However, radio observations of the surrounding H II region S222 clearly require a higher far-ultraviolet luminosity than an F star can provide (Brown, Broderick, and Knapp 1976). From the ultraviolet luminosity required to ionize S222, and bolometric luminosity required by the infrared flux, Brown *et al.* suggest B2e might be more appropriate. The strength of the H and K lines is still unexplained.

From the distances of nearby, relatively unobscured stars of undisputed spectral type, Herbig (1971) estimates the distance of the whole complex to be 800 pc. This estimate, which may be an understimate, will be used in this paper.

In addition to the H II region S222, and the reflection nebula NGC 1579, the star is surrounded by an elongated cloud of atomic hydrogen observed in the 21 cm line with the synthesis radio telescope at the DRAO (Dewdney and Roger 1982). The core of the cloud, centered on LkHα 101, has a radius of roughly 4'. A large, weak lobe extends up to 15' to the northwest of the star. Dewdney and Roger feel that the asymmetry arises because of a density gradient in the gas. The 21 cm line is strongly self-absorbed, indicating that the warm H I cloud is itself surrounded by a cold H I shell, part of which undoubtedly includes the dust clouds seen in silhouette against the reflection nebula.

The H I cloud is in turn embedded in a molecular cloud which has been mapped in the vicinity of the star by Christie, McCutcheon, and Chan (1982) in the CO (1 → 0) line with a 4' beam. The CO emission arises in a region at least 30' across east-west. Only lower limits are available for the molecular cloud size since their CO map does not extend to the cloud boundaries. The densest part of the associated dust cloud lies to the east of LkHα 101 and trends north-south, running off both ends of the maps. A ridge of enhanced CO emission and

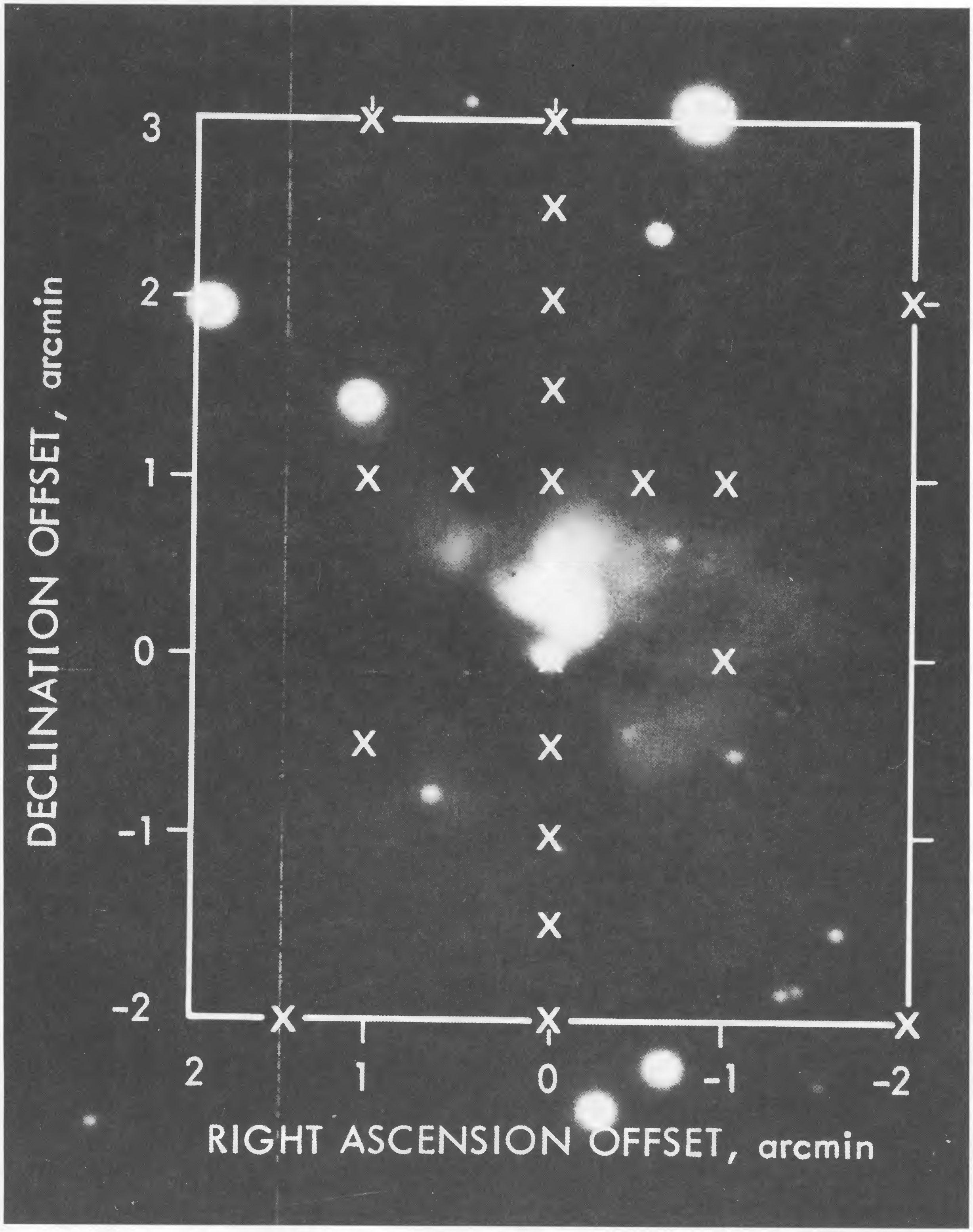


FIG. 1.—Mean intensity image of LkHα 101. The image is 10′ on a side, centered on the star. The box outlines the area mapped in CO. The crosses indicate the locations of ^{13}CO spectra.

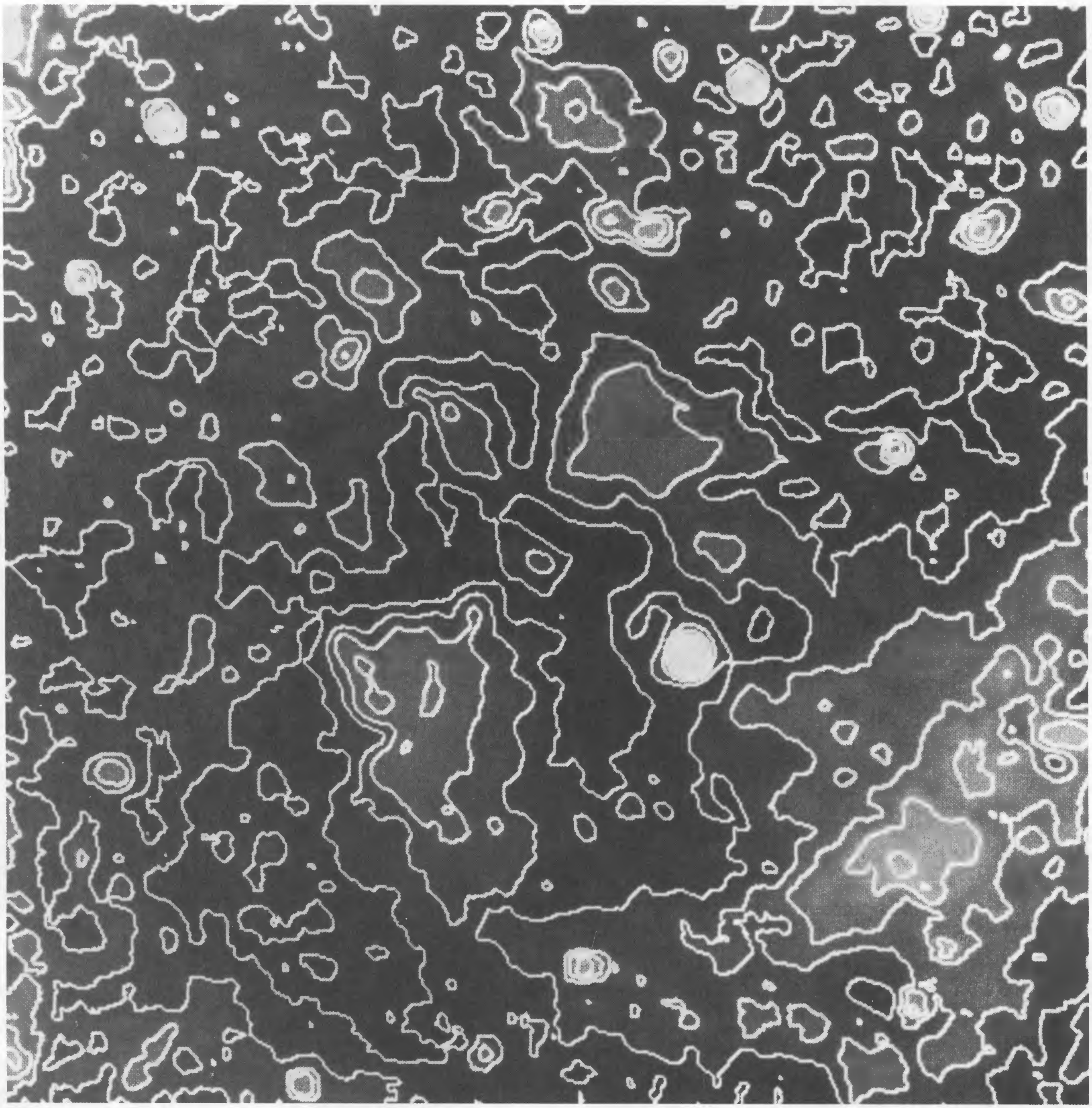


FIG. 3.—Polarization isophotes displayed on a smoothed polarization image. Each contour signifies a 2% change in polarization.

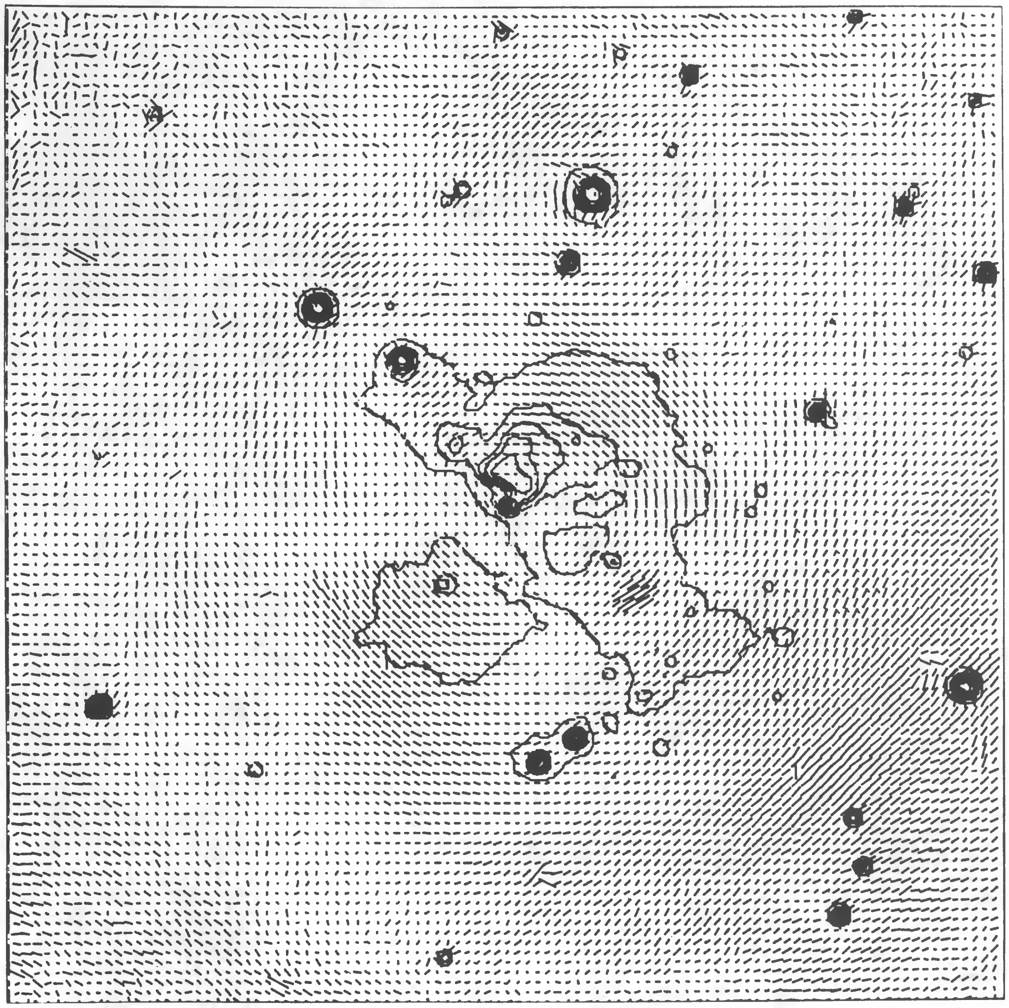


FIG. 2.—Polarization magnitudes and direction displayed as vectors. Contours are isophotes of the mean intensity image, at intervals of 25 DN (density number).

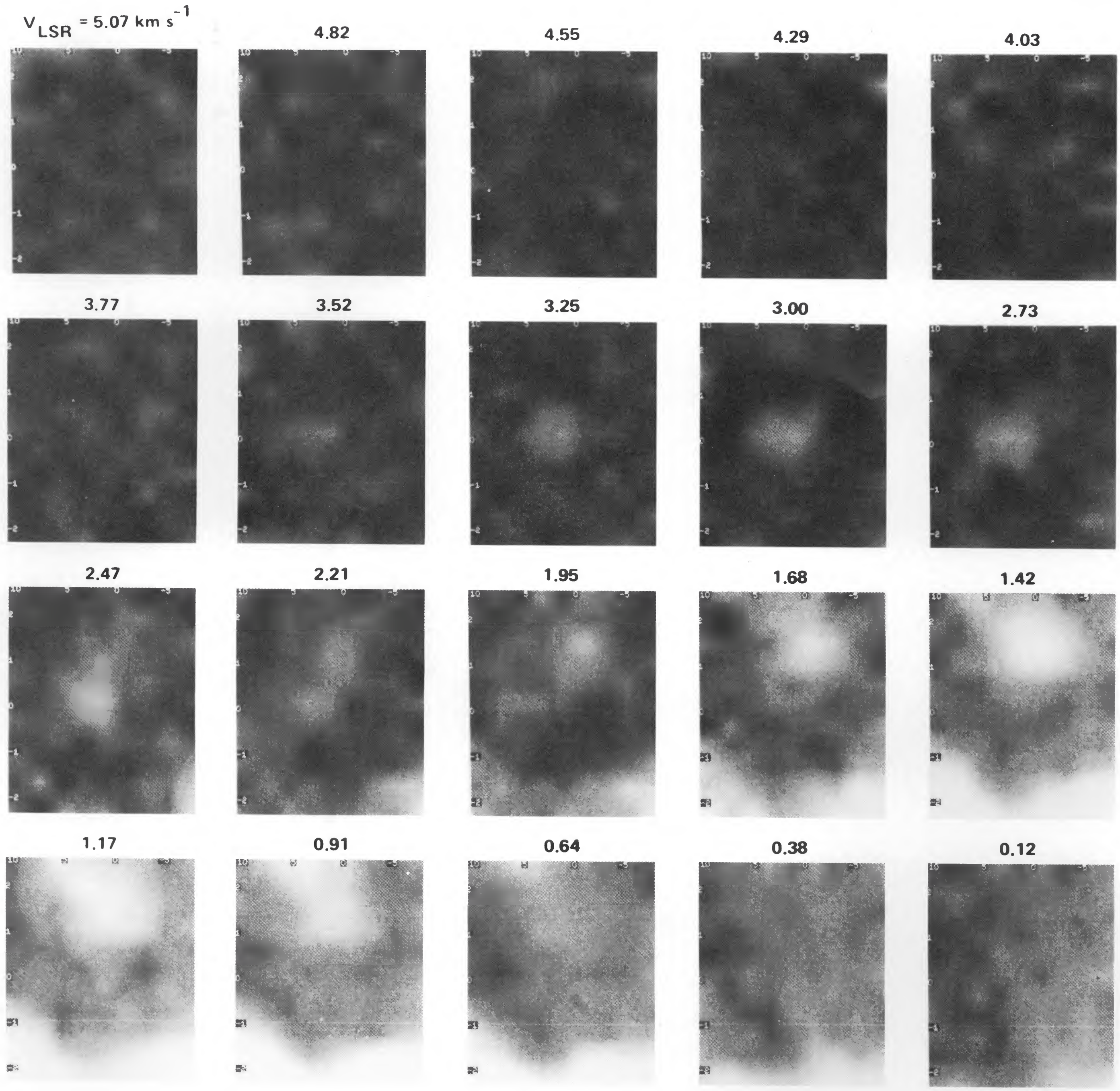
analysis. The spectra were calibrated using the chopper vane, and a linear baseline has been subtracted from each spectrum. The spectra were taken every 0.′5 with a 1′ beam in a rectangular region 4′ × 5′ centered on LkHα 101. In addition, ^{13}CO (1 → 0) spectra were taken at several positions marked in Figure 1.

Absolute pointing was checked by observations of Jupiter and Saturn. In addition, relative pointing was checked by periodically observing spectra near the central position of the map; the CO distribution varies so rapidly in this area that the relative intensities of the various spectral features could be used to point the telescope to an accuracy of about one-fifth of a beamwidth. While the relative positions within the map have such an accuracy, the position of the entire map is uncertain to about 20″. This uncertainty must be borne in mind when comparing Figure 1 and 5.

For easier comparison with the optical data, the spectra were converted at the JPL Image Processing Laboratory into a series of images showing the CO brightness distribution at each velocity. In each image, shown in Figure 5 (Plates 3 and 4), the pixel brightness at a particular right ascension and declination offset is proportional to the CO intensity at the image velocity. Since there are far more pixels in an image than CO observation points, the pixel brightness was bilinearly interpolated between the observation points.

By comparing the resulting pictures, four individual clouds can be distinguished. The *northern cloud* can be detected between 0.6 km s^{-1} and 2.0 km s^{-1}, with the strongest emission at about 1.3 km s^{-1}. The *obscuring cloud* shows emission between −2.5 km s^{-1} and −0.7 km s^{-1}, being strongest at −1.2 km s^{-1}. Two other clouds can also be seen along the southern edge of the pictures which have no counterparts in the optical image. The larger, extending across the entire southern edge of the map at 1.2 km s^{-1}, will be referred to as the *southern cloud*. The fourth cloud, −0.9 km s^{-1}, will be referred to as the *southwest cloud*.

Around 0.0 km s^{-1} the emission is diffuse and not clearly associated with any of the clouds. Preliminary comparisons with observations of the CO (2 → 1), ^{13}CO (1 → 0), and ^{13}CO (2 → 1) transitions, indicate that this gas is optically thick and self-absorbed. These new observations will be discussed fully in a future paper. Their importance for the present paper is that the velocities quoted for the clouds in the previous paragraph are larger in absolute value than the true velocities of the clouds, and that the CO (1 → 0) emission is not a good tracer of the mass distribution. Even with this qualification, the agree-



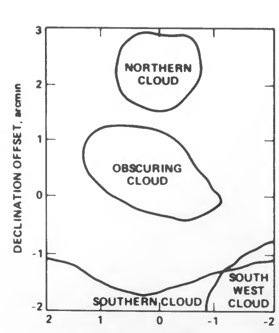


FIG. 5*a*

FIG. 5.—Intensity images of CO (1 → 0) emission around LkHα 101 at radial velocities from 5 km s^{-1} to −5 km s^{-1}. The gray scale presents 16 intensity levels between −2 K (black) to 18 K (white), in units of corrected antenna temperature (T_A*). The numbers set in at the top and left sides of each image should be ignored.

GUNN *et al.* (*see* page 303)

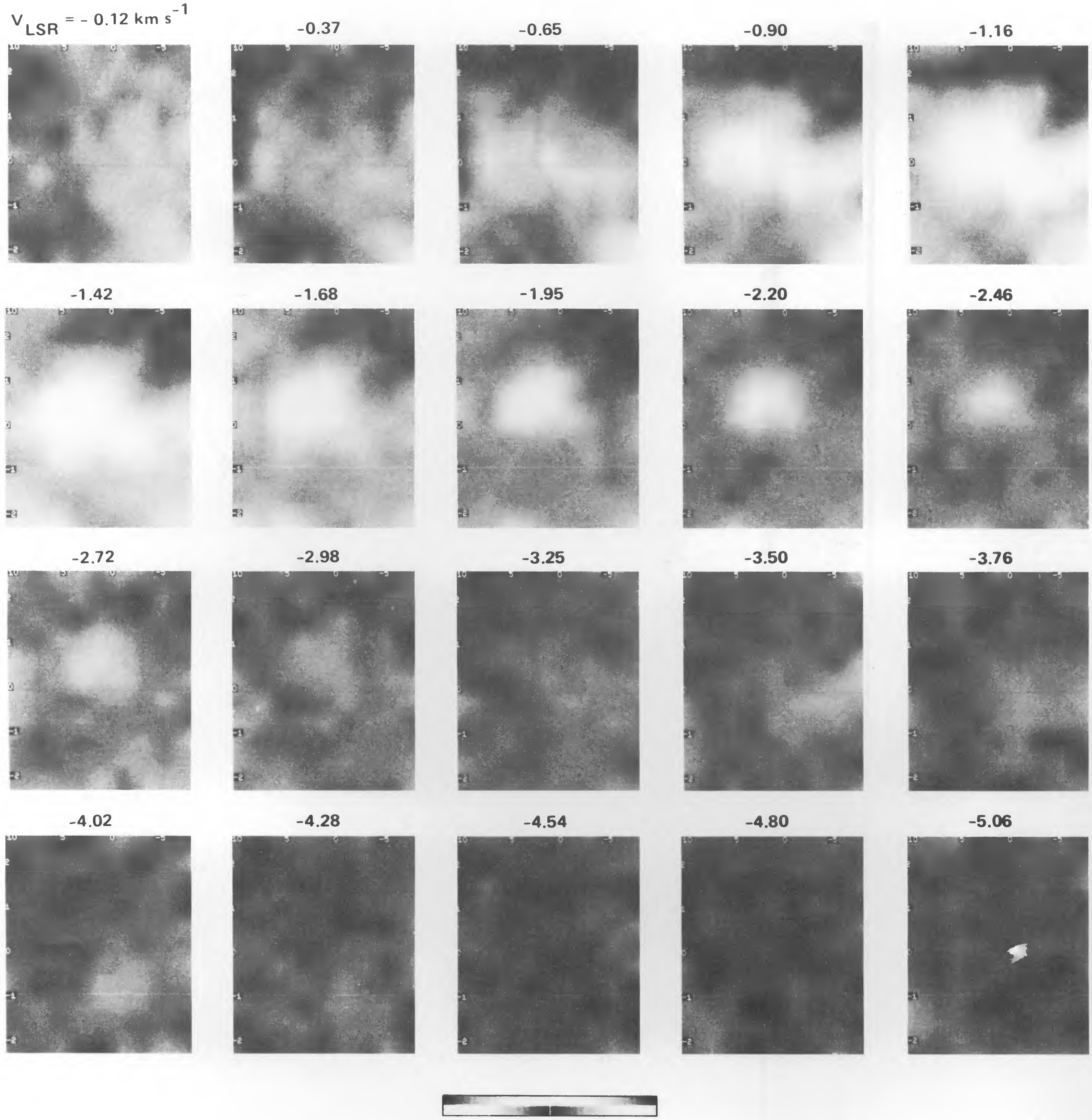


FIG. 5*b*

GUNN *et al.* (*see* page 303)

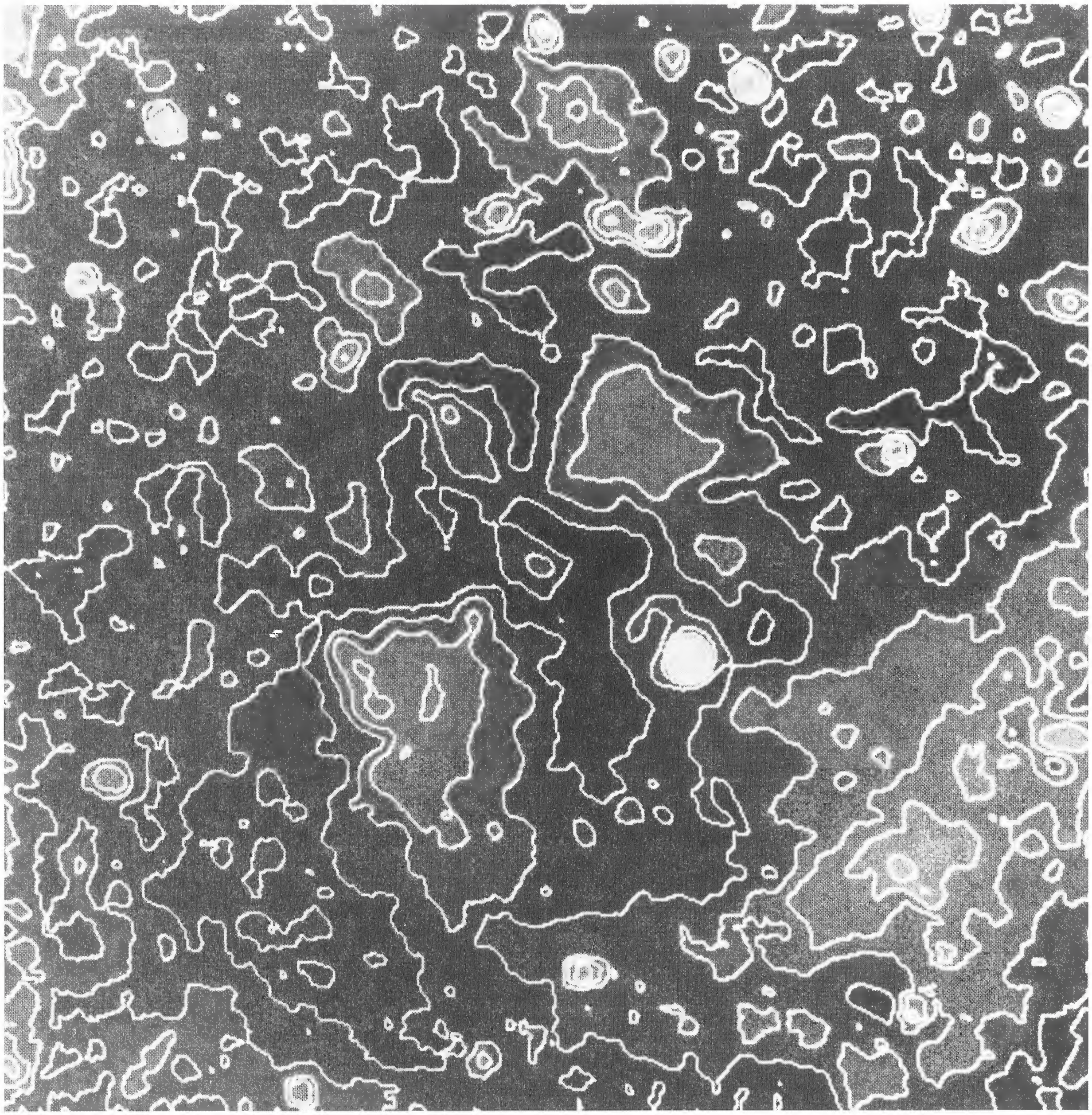


FIG. 3.—Polarization isophotes displayed on a smoothed polarization image. Each contour signifies a 2% change in polarization.

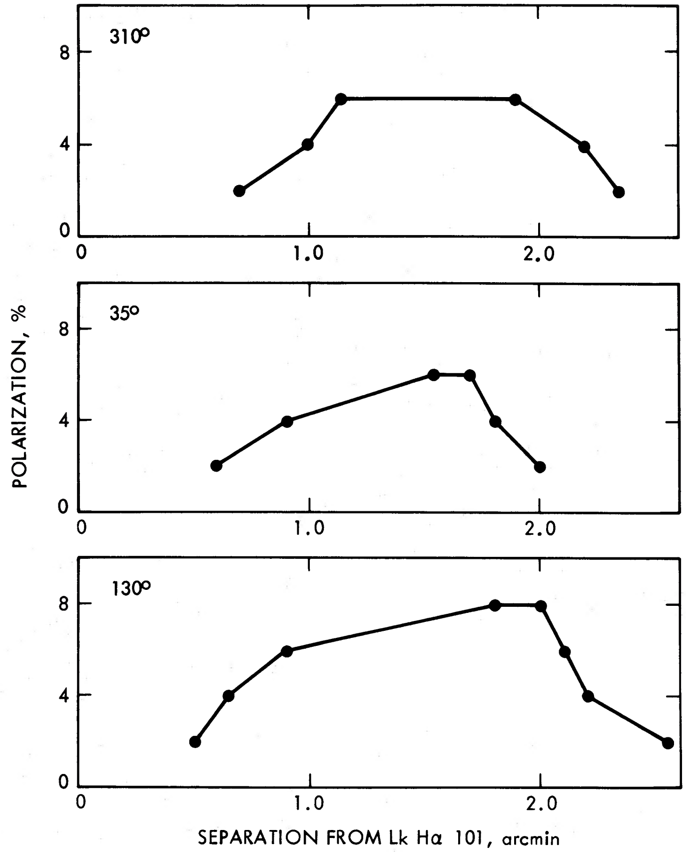


FIG. 4.—Polarization as a function of angular separation from LkHα 101 for three position angles

ment in shape and location between the optical obscuration and the CO ($1 \rightarrow 0$) emission of both the northern and the obscuring clouds justifies their treatment as independent molecular clouds.

Finally, there is some "high-velocity emission" at both positive and negative velocities in the center of the images. Because of the positional uncertainty, it is not clear whether this is more closely related to the density maximum of the obscuring cloud or to LkHα 101 itself. The emission first appears at -2.5 km s^{-1} and disappears again at 3.5 km s^{-1}, suggesting a mean velocity of 1 km s^{-1}.

The ^{13}CO emission cannot be separated into clouds as easily as the ^{12}CO emission because the spatial coverage is inadequate. However, the available data are consistent with emission from most dense portions of the northern cloud, the obscuring cloud, and the northern rim of the southern cloud. The ^{13}CO spectra in general show a single line at each location. As mentioned above, the ^{13}CO velocities are smaller in absolute value than the ^{12}CO velocities and mostly lie in the velocity range where the ^{12}CO is optically thick. Nonethless, the distribution of ^{13}CO emission in position and velocity appears to be qualitatively similar to the distribution of the strongest ^{12}CO component, which again justifies the treatment of the ^{12}CO emission components as independent molecular clouds. Figure 6 shows the ^{12}CO and ^{13}CO spectra at the position of LkHα 101. This Figure illustrates the similar signs but different absolute values of the ^{12}CO and ^{13}CO peak velocities and shows the large optical depth of the gas at small velocities.

III. DISCUSSION

a) The Reflection Nebula

The reflection nebula is best studied using the polarization maps, with one major caveat. Reflection nebulae published in the literature (Gething, Warren-Smith, and Scarrot 1982; Perkins, King, and Scarrott 1981; Schmidt, Angel, and Beaver 1978; Taylor and Scarrott 1980) typically have polarizations in the range from 20% to 60%, far higher than the 8% measured here. However, the majority of the published results are for bipolar nebulae. The nebulae surrounding LkHα 101 show no evidence of bipolar structure. The published polarization data which most closely resemble those found here are maps of H II regions such as M42 and M43 (Palister *et al.* 1977; Khallesse *et al.* 1980). For this reason, it seems likely that NGC 1579 is also an H II region, with a strong, unpolarized Hα emission diluting the polarized, scattered light.

The lowest contour in the interferometer map published by Brown, Broderick, and Knapp (1976) corresponds to an emission measure of 4000 cm^{-6} pc, assuming a gas temperature of 10,000 K. The bright rim north of LkHα 101, referred to as S222, lies substantially within this contour, and the degree of saturation of the photographic plate is consistent with Hα emission from this amount of gas. The low surface brightness of the rest of NGC 1579 requires the emission measure to be less than 1000 cm^{-6} pc. Thus, Hα emission from the extended nebula, NGC 1579, is not inconsistent with the data of Brown, Broderick, and Knapp (1976). Furthermore, the temperature of the gas in the outer nebula is likely to be lower than 10,000 K,

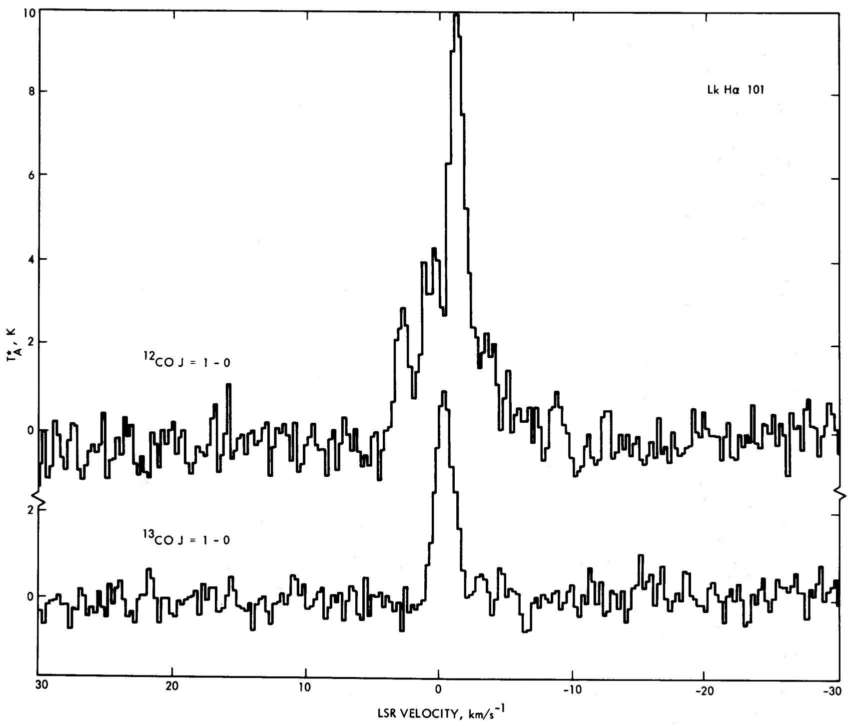


FIG. 6.—Spectra for the range ^{12}CO (1 → 0) to ^{13}CO (1 → 0) at the location of LkHα 101

which will suppress the radio continuum emission relative to Hα by a factor $T^{-0.55}$ for a fixed emission measure. Because of the potential contamination of the reflection nebula by the Hα emission, several important issues, such as the density distribution of the dust, cannot be discussed decisively without further data.

At the start of this project, it was believed that the Hα line in the spectrum of the reflection nebula was not emitted by gas in the reflection nebula but was scattered light from circumstellar gas around LkHα 101 and from S222. This certainly seems to be the case for the weaker emission lines (Herbig 1971) and would not have affected the polarization measurements significantly. Since some of the Hα line undoubtedly does arise in this way, the variation of the Hα polarization with radius will be quite different from the variation of the continuum polarization. To properly understand this region, it will be necessary to measure separately the polarization and intensity distributions of the continuum and the Hα line.

The low polarization might be due to a large dust opacity in the reflection nebula. However, the required opacity is enormous. As White (1979) has pointed out, forward scattering is strongly favored over large-angle scattering. Hence, most multiple scattering paths will have one large-angle scattering, responsible for the polarization, and several small-angle scatterings, which will not significantly affect the polarization. Consequently, raising the scattering opacity is an inefficient way to reduce the polarization. There is no evidence for such large opacities in this nebula.

As an illustration of the ineffectiveness of large opacities in suppressing the polarization of scattered light, the Red Rectangle has been observed in both the red and the blue by Perkins *et al.* (1981). The large dust opacity in the blue almost totally obscures the "horns" which are so prominent in the red, although they remain visible in the polarized intensity image. The peak polarization in the blue image of the Red Rectangle is 20%, 2.5 times greater than the peak polarization around LkHα 101. Perkins *et al.* estimate that if the unpolarized light from the peculiar red spectral feature could be subtracted, the blue and red polarizations of the Red Rectangle would be almost the same, despite the great difference in the opacities.

Although the magnitude of the polarization cannot be completely understood without more data, it is still possible to use the shape of the polarization profile to study the dust in the reflection nebula. A particularly important question which can be addressed is whether the dust lies entirely in the foreground (or background), well separated from the star or whether the dust surrounds the star. This question is motivated by the possibility that the dust in the reflection nebula may be simply a tenuous envelope surrounding the obscuring cloud, which in turn might lie some distance in front of LkHα 101.

To investigate this, a series of numerical models was constructed of reflection nebulae with various dust cloud geometries. The dust scattering properties were taken from White (1979). The intensities of the polarized and unpolarized components of the scattered light were integrated assuming single scattering in an optically thin dust cloud.

Out of all of the properties assumed for the dust, only one proved significant for this problem. White's calculations have shown that the intensity of the polarized component always varies proportionally to $\sin^2 \theta$ for forward scattering, where θ is the scattering angle and that deviations from this rule for backwards scattering are significant only at wavelengths for which forward scattering is strongly favored over backward scattering. Because of this simple behavior, the following two cases occur:

1. If the dust lies some distance b in front of (or behind) the star, then the polarization will increase quadratically with distance in the plane of the sky out to roughly b. There will be a transition zone out to several times b in which the polarization will become constant, but the scattered intensity will be

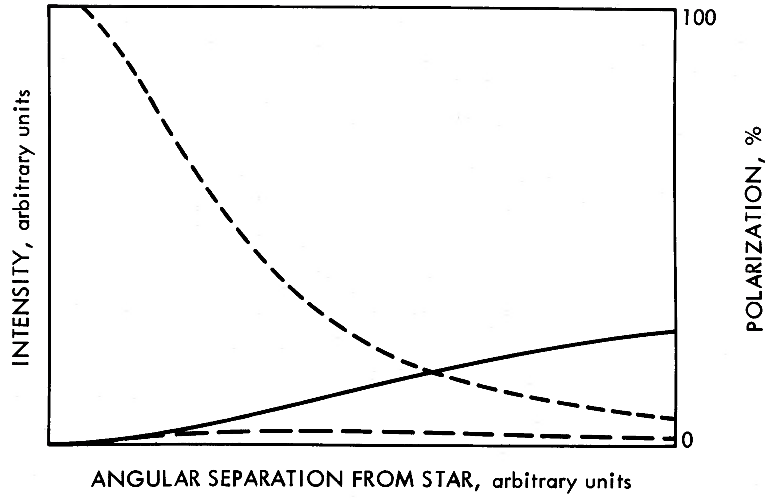


FIG. 7*a*

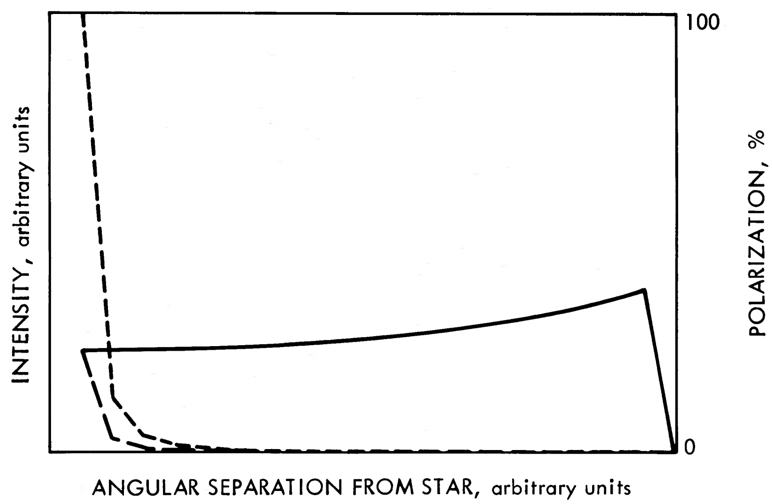


FIG. 7*b*

FIG. 7.—The intensities and polarizations as functions of distance for two model reflection nebulae. The intensity scales are arbitrary in both cases, but within each figure are the same for the mean intensity (*short dashes*) and for the polarized intensity (*long dashes*). The polarization scale (*solid curve*) always runs from 0% to 100%. The distance *b*, in arbitrary units, always runs from 0 to 1. Fig. 7*a* is for a slab of dust with geometric thickness 0.1 at a distance 0.5 in front of the star. Fig. 7*b* is for a sphere of dust with radius 1.0 centered on the star with an inverse square density distribution.

extremely faint. Figure 7*a* shows a typical example for a thin slab of dust in front of the star.

2. If the dust surrounds the star, with perhaps a power-law density distribution, then the polarization will be roughly constant across the reflection nebula. Figure 7*b* illustrates this for a spherical nebula with an inverse square density distribution of dust centered on the star.

The constancy of the polarization in the reliably measured annulus clearly favors case (2). Since 1′ at the distance of LkHα 101 corresponds to 0.23 pc, to achieve such a constant polarization with a foreground slab would require that the slab lie $\ll 0.23$ pc from the star, a conclusion little different from saying that the dust surrounds the star. Thus, regardless of the location of the obscuring cloud, the dust in the reflection nebula is directly associated with LkHα 101.

Furthermore, the dust in the reflection nebula cannot be clumped as strongly as the dust in the foreground dark clouds. Since the polarization depends strongly on the scattering angle, the polarization of the light scattered from such small clouds would vary dramatically over the face of the nebula.

b) LkHα 101 and the Obscuring Cloud

The obscuring cloud is a natural candidate for the placental cloud of LkHα 101, so it is important to decide whether the star is embedded in the cloud or not. The majority of the evidence indicates that it is not. The following points should be considered:

1. The polarization of the reflection nebula does not vary strongly with position angle. It may be clearly seen from Figure 1 that the star lies to the northwest of the main body of the obscuring cloud, and the H II region in fact peeks out from this edge of the cloud. The dust at this position angle in the reflection nebula must be illuminated fairly directly by the star. If LkHα 101 was embedded in the obscuring cloud, it would be expected that the dust at other position angles, especially to the southeast, would be only partially illuminated by the star and

would therefore show a very different polarization. The uniformity of the polarization is strong evidence that the star radiates into a uniform medium, not into a clumpy, asymmetric dust cloud.

2. The H I map of Dewdney and Roger shows no sign of constriction near the star. The gas in the H I cloud has a temperature of at least 70 K, much hotter than the molecular gas. If it were tightly confined by a surrounding molecular cloud, this would have been apparent in the H I map.

3. If the obscuring cloud actually surrounded, or even lay very close to, LkHα 101, it would be expected that radial shadowing would be apparent in the reflection nebula. In bipolar nebulae, for instance, bright rays and dark bands are common. In NGC 1579, however, these features are absent. The few dark, crooked streaks which run from the star to the edge of the nebula are almost certainly dust filaments rather than shadows.

4. The H I cloud has a velocity of 1.5 km s^{-1}, similar to the northern cloud and the southern cloud but significantly different from the obscuring cloud. If the obscuring cloud were the placental cloud for LkHα 101, the dissociated H I cloud should have had the same velocity.

5. The velocity of the obscuring cloud is constant over the entire body of the cloud (with the possible exception of the high-velocity gas—see the next section). It is conceivable that the obscuring cloud alone out of all the clouds in the region lies close enough to be affected by LkHα 101, in which case its velocity indicates that it is blowing away from the star. If LkHα 101 were embedded in the cloud, however, the parts of the cloud to the east and south would be blowing off perpendicular to the line of sight and would have a radial velocity more positive than the gas along the line of sight to the star. The constancy of the cloud velocity rules this out.

c) The Small Clouds

In the immediate vicinity of LkHα 101 the molecular gas has apparently separated into four clouds which are distinct in temperature and velocity from the cold, low-velocity foreground gas. Although LkHα 101 the does not currently reside in one of these clouds, it presumably formed in a condensation similar to the small clouds detectable today. It is important to find out which is older, the star or the clouds. If the clouds are younger than the star, they likely formed in an interaction between the newly ignited star and its placental cloud. If the clouds are older than the star, interactions between the clouds may have triggered the formation of LkHα 101.

The most direct evidence is kinematic. If the formation of LkHα 101 induced the formation of the small clouds, there should be some regularity in the motions of the clouds, either all toward or all away from the star. Since both the northern and the obscuring clouds lie in front of the reflection nebula, their radial velocities should have the same sign. Similarly, the southern and southwestern clouds lie behind the reflection nebula, so both of their radial velocities should have the opposite sign from the obscuring cloud. This is not the observed pattern. Instead, the obscuring cloud and the southwestern cloud both have negative velocities, while the northern cloud and the southern cloud both have positive velocities. Thus the cloud motions appear quite random and show neither expansion nor contraction around the star.

Furthermore, it would be difficult to accelerate the clouds gravitationally to the observed velocities. All of the clouds show significant emission at velocities of ± 2 km s^{-1}, regardless of how far from the star they lie. The free-fall velocity onto a 10 $M_\odot$ star falls below 2 km s^{-1} at a radius of 0.02 pc, corresponding to 6″. Even if the surrounding H I cloud is included, the mass only increases to 100 $M_\odot$ (Dewdney and Roger 1982), still not enough to cause the large velocities.

As mentioned in the previous section, the H I cloud observed by Dewdney and Roger (1982) has a radial velocity similar to the northern and southern clouds. Although none of these radial velocities are reliable to better than 1 km s^{-1}, this agreement suggests that all three clouds were once part of a larger cloud. Similarly, the agreement in velocity between the obscuring cloud and the southwestern cloud suggests that these were part of a second primordial cloud. These two primordial clouds, if they had survived to the present, would intersect at the current location of LkHα 101. Knitting all this speculation together, it appears that LkHα 101 could have formed in a collision between two primordial clouds whose surviving fragments are the small molecular clouds.

d) The High-Velocity Gas

There is only one clear piece of evidence for an interaction between LkHα 101 and the molecular gas. The center of the high-velocity gas (HVG) component lies very close to the star and also close to the apparent center of the obscuring cloud. This gas is certainly accelerated by LkHα 101, and the small size of the region suggests that the gas lies close to the star. Since high-velocity outflows are common around newly formed stars, it is a conservative assumption that we are seeing here a weak version of the same phenomenon. Whether the HVG is a disturbed part of the obscuring cloud or is an independent parcel of gas around LkHα 101 is not immediately apparent.

In neither case is there a problem with energetics. An early B giant can easily provide enough energy to drive a 1 km s^{-1} shock into a dense molecular cloud many parsecs away from it. Thus, some kind of shock wave, or dissociation wave, might be expected in the obscuring cloud, even if LkHα 101 lay several parsecs away. In fact, if LkHα 101 were embedded in the cloud, we would have expected a much stronger shock than this. The energetics are even easier, of course, if the HVG is close to the star and is not associated with the obscuring cloud.

The mean velocity of the HVG, estimated from its extreme velocities, is about 1 km s^{-1}. This is similar to the velocities of the northern cloud, the southern cloud, and the H I cloud, but noticeably different from the velocity of the obscuring cloud. If LkHα 101 formed out of a bridge of gas connecting the southern and northern clouds, and if the H I cloud is a remnant of that bridge, then it may be that some CO survives in the H I cloud. The HVG could lie in a disturbed region just outside the H II region. It should be noted that the high-velocity outflows seen in other regions are usually fairly symmetrical in velocity when the whole region is taken into account.

The high-velocity region is probably not more than 0.1 pc across when account is taken of the 1′ beam size in Figure 5. A 2.5 km s^{-1} shock will cross the entire high velocity region in only 4×10^4 yr. The whole obscuring cloud is not a great deal larger. A 0.5 km s^{-1} shock would completely disrupt the cloud in 5×10^5 yr. Such short characteristic times indicate that the HVG is part of a transient event very early in the history of this region. If LkHα 101 truly lies above the main sequence, it is almost surely a pre–main-sequence star.

IV. CONCLUSIONS

The gas and dust clouds surrounding LkHα 101 are at a most interesting stage in the development of the region. In addition to the star and a small surrounding H II region, there

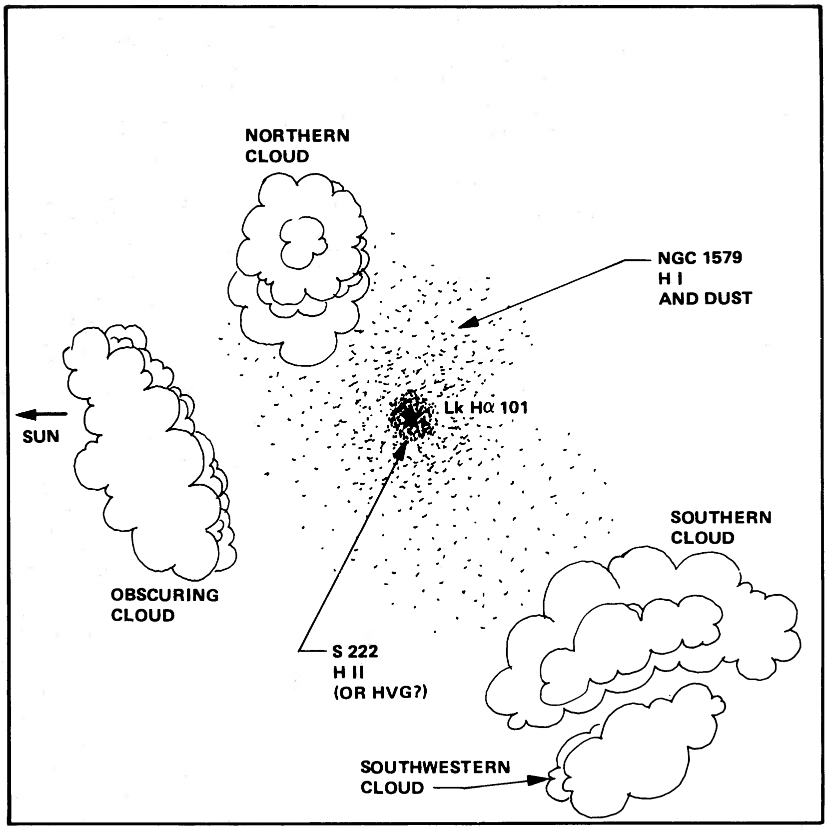


FIG. 8.—A model of the reflection nebula LkHα 101

is a large H I cloud and several small, dense molecular clouds which are the remnants of the placental cloud. Figure 8 schematically illustrates the structure deduced for the dust and gas in the region.

Despite the fact that they lie on the same line of sight, LkHα 101 is not embedded in the obscuring cloud. This is probably the most certain conclusion from this study. In fact, LkHα 101 is probably radiating into a fairly transparent hole in the middle of the molecular complex.

The dust in the reflection nebula is probably associated with the H I cloud. The analysis of the polarization is complicated by strong Hα emission, and until this Hα emission has been measured properly, it will not be possible to analyze either the dust or the Hα emitting gas unambiguously. However, even without this information, the dust appears to be distributed uniformly around LkHα 101 in position angle. Furthermore, the dust seems to lie directly around LkHα 101 itself and is not just an outer envelope of the obscuring cloud.

Because of the similarity of their radial velocities, it is possible that the northern cloud, the southern cloud, and the H I gas are physically related and may be the surviving remnants of the placental cloud for LkHα 101. In that case, the northern tip of the original cloud must have been tilted toward us since the northern cloud is visible as a dust cloud in front of the reflection nebula, and the southern cloud lies invisibly behind the reflection nebula. It is plausible that LkHα 101 formed from the collision of this placental cloud with a second cloud whose surviving fragments are the obscuring cloud and southwestern cloud.

The small, weak high-velocity region seen toward the star may arise either in shocked gas on the far side of the obscuring cloud or in disturbed gas surrounding the H II region. Although neither hypothesis can be ruled out yet, the evidence favors the latter location. In either case, the time scale of the flow is extremely short, suggesting that it has just started up in the last 10^5 yr.

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