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INFRARED IMAGING OF THE M8 HOURGLASS

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ABSTRACT

M8 is a well-observed emission nebula containing a high-surface brightness H II region, the Hourglass, toward which numerous compact infrared sources have been detected. The location and colors of these sources may offer insight into the morphology and dynamics of star formation in the M8 region. This paper present high spatial resolution ($\sim 0\farcs38$ pixel^{-1}), multiwavelength infrared broadband images of the M8 Hourglass which were obtained in order to search for compact embedded sources and to identify their spectral type. The infrared color magnitudes of two of the sources detected in our observations are consistent with the colors of early *B* stars, while a third source may be a pre–main-sequence object.

Subject headings: infrared: sources — nebulae: individual (M8, NGC 6523) nebulae: H II regions

I. INTRODUCTION

M8 (NGC 6523, S25, W9) is a well-observed emission nebula located in the Sagittarius/Carina arm of the Galaxy at a distance of 1.5 kpc (Georgelin and Georgelin 1976) containing sites of recent star formation such as the M8E complex (Simon *et al.* 1984). Near the center of the optical nebulosity is the Hourglass, a 15″ EW × 30″ NS region of high-surface brightness, containing a compact H II region exhibiting nonstandard reddening, strong 3.28 μm band emission and peculiar optical and radio morphology (Woodward *et al.* 1986). The Hourglass is mainly ionized by the O7 V star Herschel 36 (Her 36), while the extended nebulosity ($\sim 3'$ in extent) is ionized by the O stars HD 165052 and 9 Sgr (Woolf 1961).

Previous observational evidence suggested the possible presence of compact sources along the line of sight to the core of the Hourglass. Indeed, numerous point sources are visible toward the Hourglass in the 2 μm image of the M8 region obtained from rasterscan observations of Allen (1986) made with a 1″ aperture. At longer wavelengths (~ 10 μm) only two unresolved objects, IRS 1 and IRS 2 (Dyck 1977), have been detected. The location and colors of these sources may offer insight into the morphology and dynamics of star formation in the M8 Hourglass. This paper, the second (Woodward *et al.* 1986, Paper I) in a series of detailed observational investigations of this region, presents high-spatial resolution ($\sim 0\farcs38$ pixel^{-1}), multiwavelength infrared broad-band images of the M8 Hourglass, obtained in order to search for compact embedded sources and to identify their spectral type.

II. OBSERVATIONS

The near-infrared images of the Hourglass region in M8 were obtained on the Kitt Peak National Observatory (KPNO) 4 m telescope on 1985 May 10 with the University of Rochester 1–5 μm 32 × 32 Infrared CCD Array Camera (Forrest *et al.* 1985). The observing techniques and data reduction procedures are described in Forrest *et al.* (1985) and Woodward (1987). The platescale and rotation of the camera were calibrated using star pairs and star trails (obtained with the telescope drive switched off) as described in Forrest, Pipher, and Stein (1986). Repeated observations of the standard stars γ Lyra and β Boo were used to drive a flux density calibration and to estimate the seeing. We estimate an overall uncertainty of 10% in the derived flux levels. The full width half-power (FWHP) of stellar point sources, determined from the observations of the standard star β Boo, was $\sim 1\farcs2 \times 1\farcs2$ (R.A. × Decl.).

Logarithmic greyscale reproductions of the *H* ($\lambda = 1.65$ μm, $\Delta\lambda = 0.32$ μm), *K* ($\lambda = 2.23$ μm, $\Delta\lambda = 0.41$ μm), and *L′* ($\lambda = 3.75$ μm, $\Delta\lambda = 0.81$ μm) broad-band images are presented in Figure 1*a*–1*c* (Plates 9–11). The flux density isophotes of the M8 Hourglass field derived from the broad-band images are shown in Figures 2*b*–2*d*. Figure 2*a* labels the sources discussed in this paper, including the main exciting source of the Hourglass, Her 36, and the five point sources, designated KS 1 through KS 4 in order of increasing right ascension measured eastward of Her 36, detected in our 2 μm image. A fifth source, KS 5, in the upper north part of the region imaged in our observations also is labeled. However, KS 5 was only marginally detected at the 3 σ level. The position of each source, determined relative to Her 36, and the observed integrated magnitude in an equivalent 3″ octagonal aperture in each bandpass, uncorrected for extinction, are given in Table 1.

III. DISCUSSION

There is good overall correspondence between sources seen in our *K* image, and those detected at *I* and *K* by Allen (1986). The source KS 1 is located along the line of sight to the optical nebulosity surrounding Her 36, while the sources KS 3 and KS 4 are along the line of sight to the "waist" of the Hourglass. Since at optical wavelengths the nebula has a suggestive "bipolar" morphology, the location of KS 3 and KS 4 near the apex of the optical fans (the waist) is intriguing. For

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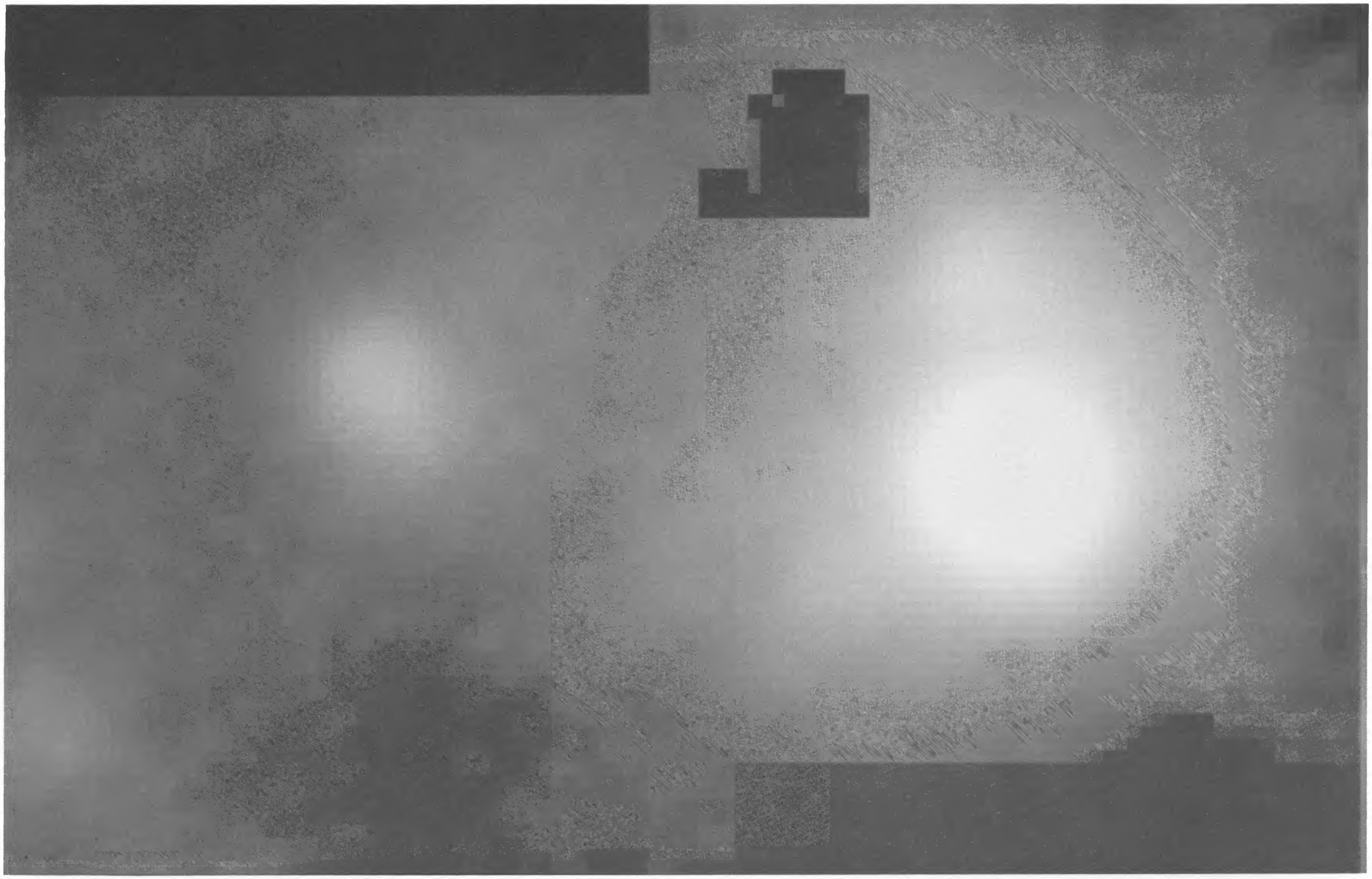

FIG. 1*a*

FIG. 1.—Logarithmic greyscale images of the M8 Hourglass region obtained with the University of Rochester Infrared CCD Array Camera on the NOAO-KPNO 4 m telescope. The grey levels are scaled from the 5 σ signal-to-noise level (*black*) to the peak contour value (*white*) plotted in the respective isophote maps presented in Figs. 2*b*–2*d*. The field-of-view and orientation of each greyscale image is the same as that of Fig. 2*b*–2*d*. The field-of-view and orientation of each greyscale image is the same as that of Fig. 2. (*a*) The *H* (1.65 μm) image. (*b*) The *K* (2.23 μm) image. (*c*) The *L*′ (3.75 μm) image.

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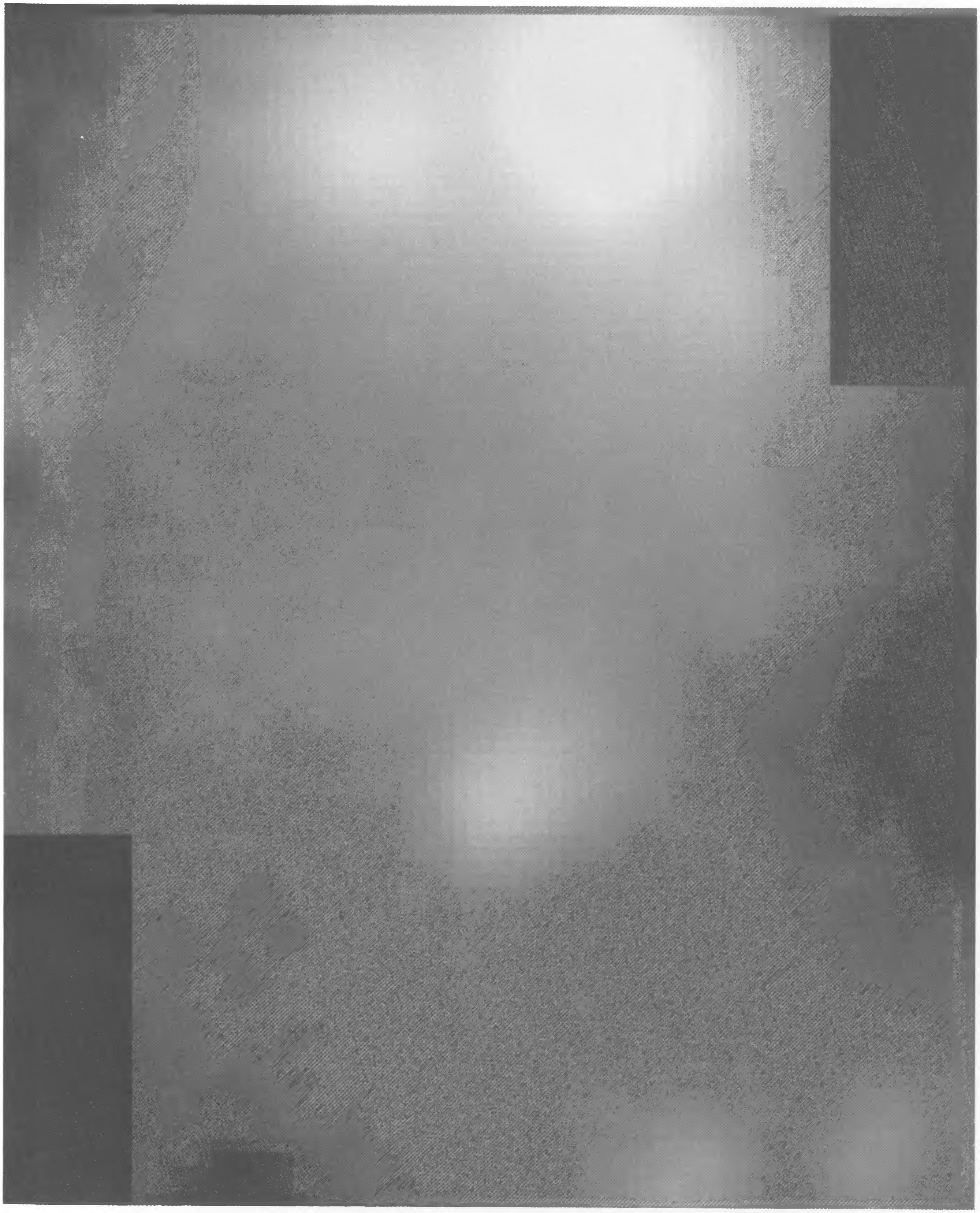

FIG. 1*b*

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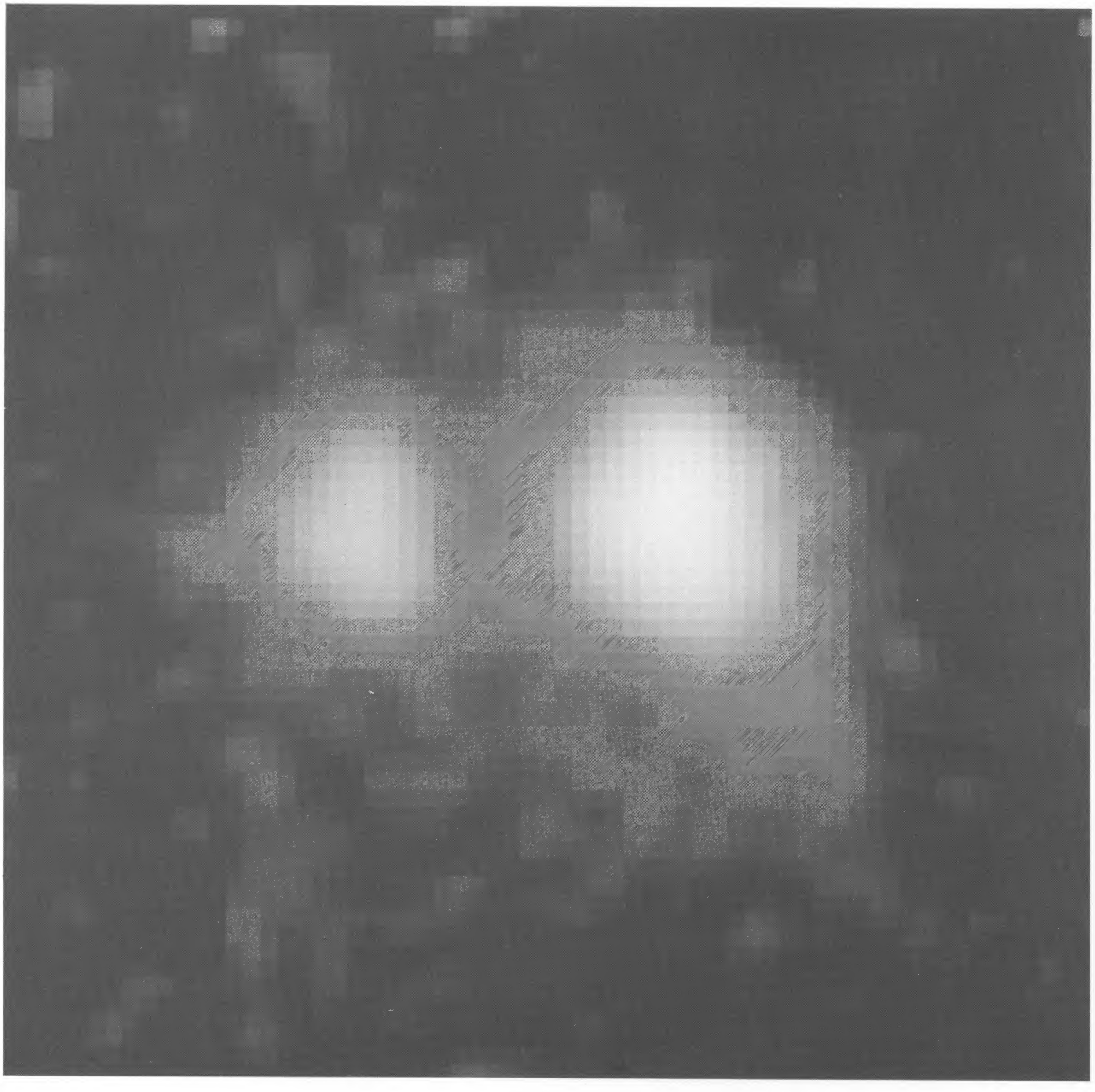

FIG. 1*c*

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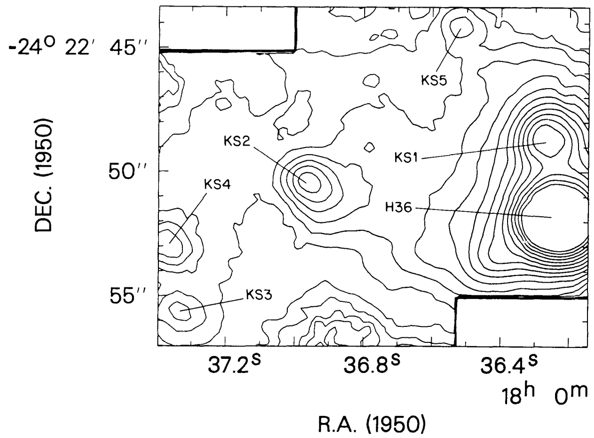

FIG. 2a

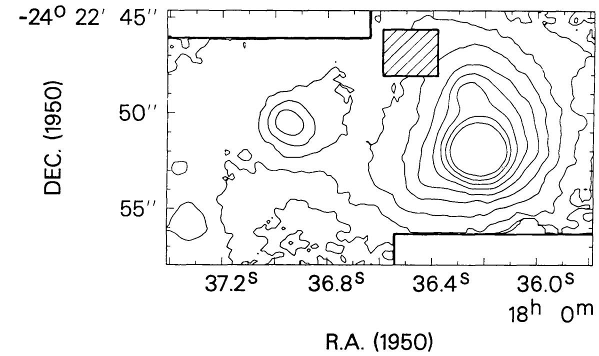

FIG. 2b

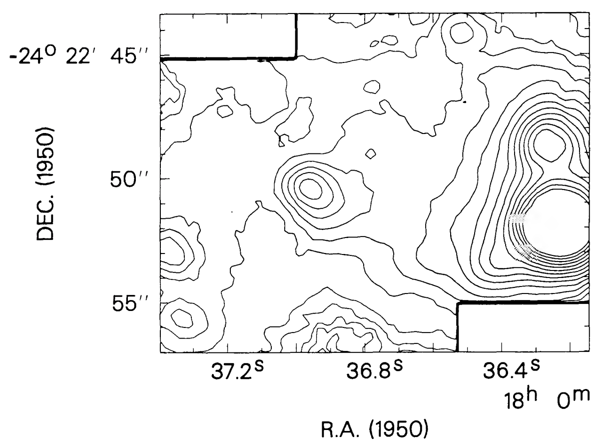

FIG. 2c

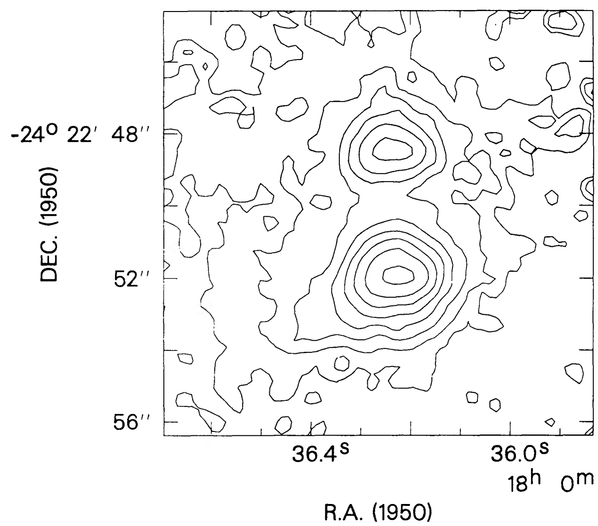

FIG. 2d

FIG. 2.—The flux density isophotes of the M8 Hourglass field from the near-infrared, broad-band images obtained with the Rochester Infrared CCD Array Camera on the NOAO-KPNO 4 m telescope. The blank areas outside the heavy solid line were not imaged. The five point sources and Her 36 are labeled with the nomenclature used in this paper (*a*), which is based on the *K* map. (*b*) The broad-band *H* (1.65 μm) flux density isophotes. The contour lines denote values from 2.7 mJys arcsec^{-2} to 172.6 mJys arcsec^{-2}, with contour intervals separated by a ratio of 1.585 ($\sim$0.5 mag). The approximate 1 σ surface brightness in the image estimated from the rms noise per pixel at the periphery is $\sim$0.5 mJys arcsec^{-2}. The cross hatch area northeast of Her 36 contain no data. (*c*) The broadband *K* (2.23 μm) flux density isophotes. The contour lines denote values from 2.7 mJys arcsec^{-2} to 171.6 mJys arcsec^{-2}, with contour intervals separated by a ratio of 1.259 ($\sim$0.25 mag) to emphasize the point sources in the diffuse nebulosity. The approximate 1 σ surface brightness in the image estimated from the rms noise per pixel at the periphery is $\sim$0.9 mJys arcsec^{-2}. (*d*) The broad-band *L′* (3.75 μm) flux density isophotes. The contour lines denote values from 44.7 mJys arcsec^{-2} to 1122.2 mJys arcsec^{-2}, with contour intervals separated by a ratio of 1.585 ($\sim$0.5 mag). The approximate 1 σ surface brightness in the image estimated from the rms noise per pixel at the periphery is $\sim$8.9 mJys arcsec^{-2}. Only the sources Her 36 and KS 1 are visible in the field.

reference, the positions of 2 μm sources detected in our observations, as well as the 11 μm sources IRS 1 and IRS 2 (Dyck 1977) are plotted on the 5 GHz radio interferometric continuum isophotes (Woodward *et al.* 1986) in Figure 3.

a) KS 3 and KS 4

The two sources, KS 3 and KS 4, are located along the line of sight toward the apex of the optical bicone of the Hourglass. At *K* both KS 3 and KS 4 have comparable magnitudes, yet both are $\sim$4 mag fainter than Her 36 (Table 1) which suffers 4 mag of visual extinction (Hecht *et al.* 1982). KS 3 is slightly redder than Her 36, and KS 4 is slightly redder than KS 3 based on their $H-K$ color magnitudes. From visual inspection of an (uncalibrated) *I* image (Allen 1986), KS 3 appears faint compared with Her 36, while KS 4 was not detected. Thus, KS 4 is indeed observed to be redder than KS 3. Further, it is unlikely that KS 4 and KS 3 are just density enhancements in the ionized gas associated with the eastern radio intensity maxima. The 5 GHz continuum radio flux density (estimated from Fig. 3) in a equivalent 3″ beam at the position of KS 3 is $\sim$35.1 $\pm$ 1.8 mJy, while that estimated for KS 4 is $\sim$43.9 $\pm$ 2.2 mJy. Adopting a value of $\sim$0.27 (Woodward 1987; Willner, Beckin, and Visvanathan 1972) for the ratio of the optically thin *K* band flux density due to thermal gas emission processes to the 5 GHz radio flux density, we find that for both sources the observed *K* band flux density exceeds that due to thermal gas emission alone. For KS 3 the excess *K* emission is 7.1 $\pm$ 1.0 mJy; for KS 4 7.5 $\pm$ 1.1 mJy. The estimated value for the residual emission is only a lower limit because the observed *K* band flux densities have not been dereddened.

The origin of this excess emission can either be due to scattered light, hot dust emission, or a stellar-type object along the line of sight. Since these objects are pointlike in our infrared images and the *I* and *K* band images of Allen (1986), with

TABLE 1

POSITIONS AND OBSERVED MAGNITUDES OF SOURCES DETECTED IN THE M8 HOURGLASS

Source Name	Position[a] R.A. (1950)	Decl. (1950)	Magnitudes[b] H 1.65 μm	K 2.23 μm	L' 3.75 μm
Her 36	36^{s}23	51″9	7.9	7.5	6.3
KS 1	36.27	48.6	10.7[c]	9.4	7.2
KS 2	36.96	50.6	11.3	10.6	...
KS 3	37.35	55.9	12.2	11.4	...
KS 4	37.39	53.1	12.5	11.3	...

[a] All source positions (±) 0″1 are determined from the K band images, relative to Her 36. The astrometric position of Her 36, $\alpha(1950) = 18^h00^m36^s23$, $\delta(1950) = -24°22'51''9$ is from Woodward *et al.* (1986) and van Aletna and Jones (1972).

[b] Measured magnitude (±0.2 mag) in an effective 3″ circular beam.

[c] Magnitude (±0.3 mag) at this wavelength estimated from differential photometry using Her 36.

intensity profiles similar to those measured for standard stars, we suspect that these sources are compact, discrete objects. Adopting a $\lambda^{-0.8}$ extinction law (Johnson 1967) for the Hourglass region and assuming these objects are stellar, an estimate of possible spectral types and visual extinctions can be made using stellar intrinsic colors (Koornneef 1983; Johnson 1966).

We find that the observed H and K band magnitudes are consistent with KS 3 being slightly earlier than B5 V (but later than BO) with a visual extinction, $A(V)$, ≥5 mag (≤12 mag). By this model, the predicted I magnitude would be ~5 mag fainter than that of Her 36. Such a star would supply less than 10^{-5} the ionizing photons of Her 36 based on the stellar

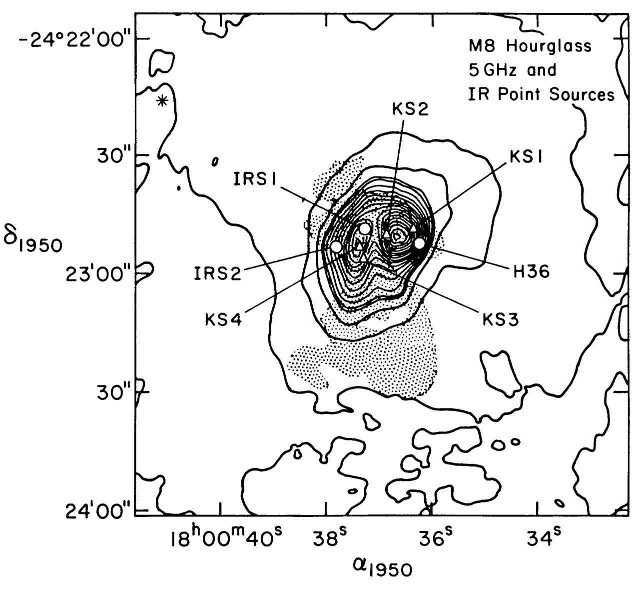

FIG. 3.—The positions of the four K band (≥3 σ detection) infrared point sources in the M8 Hourglass, KS 1 through KS 4, plotted on the 5 GHz radio interferometric continuum isophotes (Woodward *et al.* 1986). Dotted in on top of the radio isophotes is the outline of the region of highest optical surface brightness taken from a blue photograph of the Hourglass. The lightly dotted area designates the main body of the Hourglass, with the surface brightness falling off to the north and south (*heavier dots*). The positions of the near infrared K band sources are designated by open triangles, while the positions of the 11 μm sources of Dyck (1977) and Her 36 are designated by open circles. The position of Cordoba 12403 is indicated with a star.

models of Panagia (1974). The observed H and K magnitudes of KS 4 can be replicated either by a hot star (~B0 V) attenuated by 12.4 mag of visual extinction, or by a cool star with the magnitudes and colors of a K0 III star, attenuated by 8.3 mag of visual extinction. Both models predict that KS 4 would be ~7 mag fainter than Her 36 at I. Neither object is likely to affect the ionization structure of the compact double-lobed, H II region which is dominated by the O7–8 V star Her 36 (Woodward *et al.* 1986; Hecht *et al.* 1982).

Unfortunately, the $H-K$ color magnitudes for main sequence stars are not sensitive indicators of spectral type. Furthermore, Allen (1986) does not give photometrically calibrated magnitudes for these sources, thus the models for spectral type deduced above are only approximate. A more precise determination of the spectral types for KS 3 and KS 4 can be made when additional color data become available. However, in light of our observations, we can tentatively assess which interpretation, especially of KS 4, is more probable. We prefer the interpretation that KS 4 is a highly attenuated hot star. While very young (≤10^5 years) 2 $M_\odot$ pre–main-sequence (PMS) stars occupy the K0 III region of the H-R diagram (Cohen and Kuhi 1979), PMS stars typically exhibit infrared excess due to circumstellar emission. Without another color measurement, we cannot assess whether KS 4 is a less attenuated, lower luminosity PMS star with circumstellar emission contributing to its red color. If the object is an evolved K0 III star, it would not be associated with the M8 Hourglass star-formation region (≤2 × 10^6 yr), and its intriguing position in the Hourglass would be merely fortuitous.

b) KS 2

The object, KS 2, has an identical $H-K$ color to Her 36, but it is 3.4 mag fainter. If it suffers the identical extinction to Her 36 because it is obscured by the same foreground cloud, it could be a B4 V star. Its location is ~3″ E of the western radio lobe. Again, this star does not affect the ionization of the region substantially.

c) KS 1

The source KS 1 (Her 36B, Allen 1986) is ~3″3 north and 0″6 east of Her 36. The isophote maps of the observed K and L' surface brightness (Figs. 2*a* and 2*c*) clearly show that KS 1 is enveloped in the nebulosity seen along the line of sight toward Her 36. Also, evident in these maps is a distention of the K and L' isophotes toward the southeast, away from Her 36, giving the high surface brightness region surrounding Her 36 a "pear-shaped" appearance. There is no evidence of an obscuring disk of material surrounding Her 36, such as that suggested by Lightfoot *et al.* (1984) or Elliot *et al.* (1984) that gives rise to the optical morphology of the nebula.

The detection of KS 1 in the optical nebulosity surrounding Her 36 could explain the anomalous value of $A(V)/E(B-V)$ seen along the line of sight to this star (Johnson 1967). Previous measurements to determine the IR dependence of $A(\lambda) - A(V)$ would include the two objects in the measurement beam, and KS 1 is quite red. The $H-K$ colors of KS 1 are intermediate between KS 3 and KS 4. On this basis alone, we might interpret KS 1 as another heavily obscured hot star. However, KS 1 is quite bright at L' (Table 1). The observed greybody $K-L'$ color temperature of KS 1 is ~1000 K, while the greybody $L'-M'$ (Woodward *et al.* 1990) color temperature is ~800 K. Thus this source may either be a possible pre–main-sequence object, or if it is not stellar, a dust knot seen in scattered light from Her 36.

As Allen (1986) pointed out, the separation distance between Her 36 and KS 1 are comparable to those found for the Trapezium stars in Orion, perhaps indicating that KS 1 and Her 36 are members of a multiple system with Her 36 close to the main sequence, and KS 1 still evolving on its Hayashi track. Recently, several young stars such as T Tau, (Dyck, Simon, and Zuckerman 1982) and GL 961 (Lenzen, Hodupp, and Reddmann 1984) have been observed to have considerably redder, lower luminosity companions. The observed $K-L'$ color magnitude of KS 1 (2.2 mag) is comparable to that observed for other candidate PMS objects such as L1551-IRS 5, $K-L' = 3.1$ mag (Moneti *et al.* 1988).

IV. SUMMARY

The detection of pointlike stellar sources toward the core of the M8 Hourglass suggests, like the Orion complex, that M8 may contain a Trapezium-like stellar cluster of hot stars in which Her 36 is the analog of $\Theta^1 C$, providing most of the ionizing photons. Estimates of spectral type from the observed infrared broad-band colors suggests that the two sources, KS 3 and KS 4, located along the line of sight to the waist of the Hourglass may be early B stars. The nature of the source KS 1, located just north of Her 36, is more problematic. Based on greybody temperature estimates and its projected separation (on the plane of the sky) from Her 36, KS 1 may be a cool pre–main-sequence object. However, longer wavelength broad-band color magnitude data (M', N, and Q) observations of KS 1 may permit us to determine the precise nature of this object. With additional high spatial-resolution imaging observations at all 1–5 μm broad-band wavelengths, the M8 Hourglass region may prove to be an excellent laboratory for studying detailed morphology of regions of massive star formation, and provide new data on quantitative aspects of star formation, in particular the initial mass function in this region of the galaxy.

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REFERENCES

Allen, D. A. 1986, *M.N.R.A.S.*, **219**, 35.
Cohen, M., and Kuhi, L. V. 1979, *Ap. J. Suppl.*, **41**, 743.
Dyck, H. M. 1977, *A.J.*, **82**, 192.
Dyck, H. M., Simon, T., and Zuckerman, B. 1982, *Ap. J. (Letters)*, **255**, L103.
Elliot, K. H., Goudis, C., Hippelein, H., and Meaburn, J. 1984, *Astr. Ap.*, **138**, 451.
Forrest, W. J., Moneti, A., Woodward, C. E., Pipher, J. L., and Hoffman, A. 1985, *Pub. A.S.P.*, **97**, 183.
Forrest, W. J., Pipher, J. L., and Stein, W. 1986, *Ap. J. (Letters)*, **301**, L49.
Georgelin, Y. M., and Georgelin, Y. P. 1976, *Astr. Ap.*, **49**, 57.
Hecht, J., Helfer, H. L., Wolf, J., Donn, B., and Pipher, J. L. 1982, *Ap. J. (Letters)*, **236**, L39.
Johnson, H. L. 1966, *Ann. Rev. Astr. Ap.*, **4**, 193.
———. 1967, *Ap. J.*, **147**, 912.
Koornneef, J. 1983, *Astr. Ap.*, **12**, 84.
Lenzen, R., Hodupp, K.W., and Reddmann, T. 1984, *Astr. Ap.*, **137**, 365.
Lightfoot, J. F., *et al.* 1984, *M.N.R.A.S.*, **208**, 197.
Moneti, A., Pipher, J. L., Forrest, W. J., and Woodward, C. E. 1988, *Ap. J.*, **327**, 870.
Panagia, N. 1974, *A.J.*, **78**, 929.
Simon, M., Cassar, L., Fisher, J., Massi, M., and Sanders, D. 1984, *Ap. J.*, **278**, 170.
van Alenta, W. F., and Jones, B. F. 1972, *Astr. Ap.*, **20**, 425.
Willner, S. P., Becklin, E. E., and Visvanathan, N. 1972, *Ap. J.*, **175**, 699.
Woodward, C. E. 1987, Ph.D. thesis, University of Rochester.
Woodward, C. E., *et al.* 1986, *A.J.*, **91**, 870 (Paper I).
Woodward, C. E., Pipher, J. L., Shure, M. A., and Forrest, W. J. 1990, in preparation.
Woolf, N. J. 1961, *Pub. A.S.P.*, **73**, 206.

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