THE ASTROPHYSICAL JOURNAL, 408:L101–L103, 1993 May 10

NEAR-INFRARED DISCOVERY OF THE L810 NEBULA ILLUMINATOR

JOÃO LIN YUN
Department of Physics, University of Lisbon, Campo Grande, Ed. C1, Piso 4, 1700 Lisboa, Portugal

DAN P. CLEMENS
Astronomy Department, Boston University, 725 Commonwealth Avenue, Boston, MA 02215

MARK J. MCCAUGHREAN
Max-Planck-Institut für Astronomie, Königstuhl 17, W-6900 Heidelberg, Germany

AND

MARCIA RIEKE
Steward Observatory, University of Arizona, Tucson, AZ 85721
Received 1993 January 28; accepted 1993 February 25

ABSTRACT

As part of a deep near-infrared imaging survey for infrared point sources in Bok globules, we have discovered the illuminator of the optical reflection nebula seen toward the Bok globule L810. The illuminator (L810 IRS) is located at the position predicted by Scarrott, Rolph, & Tadhunter from analysis of their optical polarimetry. This source is very red ($J-K \sim 3.9$) and bright ($m_K = 10.7$), and has an estimated bolometric luminosity of 890 $L_\odot$. Additionally, we found a near-infrared nebula which extends 20″ symmetrically to the north and to the south of L810 IRS, exhibiting an hourglass shape. Both the morphology and the orientation of the near-infrared nebula are in good agreement with the morphology and orientation of the high-velocity molecular outflow associated with L810. Finally, we found a near-infrared jetlike structure whose axis is collinear with L810 IRS. Together, these findings indicate that L810 IRS is likely to be a deeply embedded, very active intermediate-mass young stellar object within the L810 cloud.

Subject headings: infrared: stars — ISM: individual (L810) — ISM: jets and outflows — reflection nebulae — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

Bok globules are nearby small dark clouds of cold gas and dust usually displaying simple shapes. The dark cloud Lynds 810 ($\alpha_{1950} \sim 19^h43^m21^s.9$, $\delta_{1950} \sim 27°43'40''$) is a relatively large Bok globule which displays an extended optical reflection nebula on the Palomar Observatory Sky Survey plates. Star formation in this cloud has been studied since Herbst & Turner (1976) indicated that the reflection nebulosity observed in the center of L810 could be a sign of active star formation. Subsequently, Neckel et al. (1985) probed the gas and dust in this cloud via radio observations of ammonia transitions and H_2CO absorption lines. They estimated a distance to L810 of 1.5–2.0 kpc and derived a total cloud mass of 800 $M_\odot$ and a total cloud luminosity of 350 $L_\odot$. Turner (1986) derived a distance of 2.5 kpc based on star counts and on association of L810 with Vul OB1. Xie & Goldsmith (1990) discovered and mapped a high-velocity CO outflow which has a north-south axis and is associated with L810.

Recently, Neckel & Staude (1990), in an optical CCD imaging and polarimetric study, concluded that L810 could be harboring 12–15 stars. They argued that several of these stars could be associated with individual cometary nebulae. Furthermore, they proposed that star 7 (Neckel & Staude nomenclature) was the main illuminator of the L810 nebula. However, Scarrott, Rolph, & Tadhunter (1991) independently obtained an optical polarization map of the nebula which did not confirm the conclusions of Neckel & Staude. Instead, Scarrott et al. determined that only one source could be the nebula illuminator, and they derived a position for the illuminator where no optical star could be seen and named this invisible source L810 IRS. Their location was about 3″.5 to the northwest of star 7.

We have conducted a near-infrared imaging survey of a sample of Bok globules containing *IRAS* point sources (young stellar object candidates; Yun & Clemens 1990; Yun 1992). As part of this survey, we obtained deep J, H, and K images toward L810. In this paper we present isophote maps of the central region of L810, in which near-infrared nebulosity can be seen. The maps reveal the hourglass morphology of this near-infrared nebula and the presence of a very red near-infrared point source located at the position predicted by Scarrott et al. (1991).

This near-infrared source has no optical counterpart. Its near-infrared colors indicate that it is likely to be young and deeply embedded in the cloud. Thus, we believe we have discovered the near-infrared object responsible for the optical and infrared nebular illumination and the high-velocity outflow associated with L810. We have also found what appears to be a jet emanating from the core of L810. The jet axis is collinear with the near-infrared point source.

In the next sections, the near-infrared observations and data reduction are described and the results are presented and discussed. We conclude with a summary of our findings.

2. OBSERVATIONS AND DATA REDUCTION

Our near-infrared (J, H, and K bands, i.e., $\lambda = 1.25$, 1.65, and 2.2 μm) survey of point sources in Bok globules was carried out during 1991 May 22–27 using the University of

Arizona NICMOS 3 infrared array camera (Rieke et al. 1989; Thompson et al. 1989) on their Mount Bigelow 1.5 m telescope. We obtained J-, H-, and K-band images toward 15 Bok globules contained in the Clemens & Barvainis (1988) catalog of small molecular clouds. The NICMOS 3 array contains 256 × 256 pixels, and was used at a plate scale of 0.″9 pixel^{-1}, resulting in a field of view of 3.′8 × 3.′8 on the sky. For each globule, we obtained a set of 3 × 3 dithered frames. Each frame overlapped the previous one by 2′, resulting in a total covered area of about 7.′5 × 7.′5. The integration time per frame was 120 s at J, and 60 s at H and at K.

By median filtering across each stack of nine dithered images, stars were removed and a sky frame was obtained. This sky frame was subtracted from each of the nine data images. A set of dome flats were then used to flat-field the data images (except for the H band, where no dome flat was available. The H-band images were flat-fielded using the sky frames). The final flat-field images were subsequently corrected for the presence of bad pixels and mosaicked, co-adding the overlapping regions. We restricted our attention to these overlapping regions which formed a central area of about 4.′5 × 4.′5, which has reduced background noise level σ compared with the remaining area. The values of σ are about 21.5 mag arcsec^{-2} in the J-band images, 20.5 mag arcsec^{-2} in the H-band images, and 20 mag arcsec^{-2} in the K-band images. All the magnitudes are in the Johnson standard system (Johnson, MacArthur, & Mitchell 1968). Calibration was performed by observing stars from the list of Elias et al. (1982).

3. RESULTS AND DISCUSSION

3.1. *Exciting Star*

Figure 1 shows the near-infrared K-band image obtained toward L810. It covers an area of about 1.′1 × 1.′1 toward the young stellar object candidate IRAS 19433+2743 (Yun 1992). In this figure there is a very extended infrared nebula, some of which corresponds to an extended optical reflection nebula on the Palomar Observatory Sky Survey (POSS).

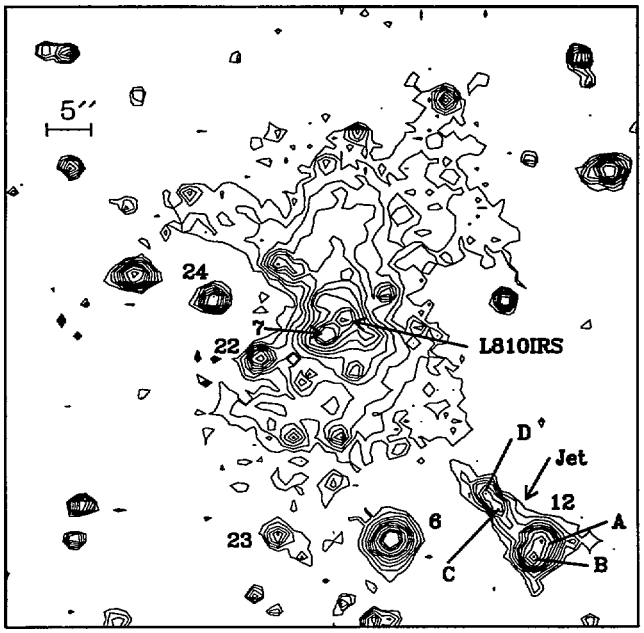

FIG. 1.—Isophotes of near-infrared emission (K band) from L810, covering an area of about 1.′1 × 1.′1. The first contour corresponds to a surface brightness of 18.7 mag arcsec^{-2}, and the contours are stepped by 0.5 mag arcsec^{-2}. The extended nebula exhibits a symmetric hourglass shape in this image. In the corresponding J- and H-band images, the northern part of the nebula is absent. Star numbers are those of Neckel & Staude (1990). The near-infrared source L810 IRS, predicted by Scarrott et al. (1991), is indicated by an arrow. There is also a previously unseen jetlike feature which exhibits multiple structures.

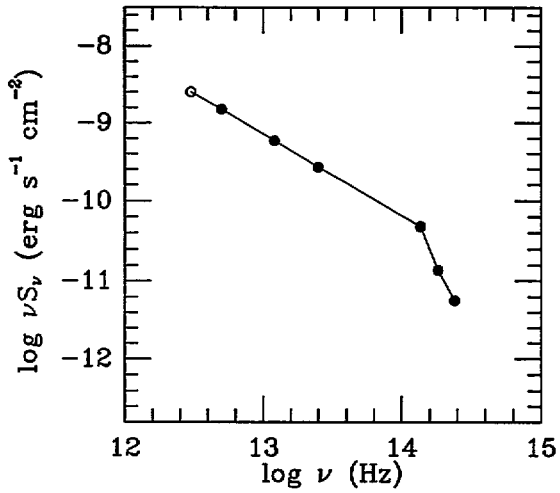

FIG. 2.—Broad-band spectral energy distribution of L810 IRS +IRAS 19433+2743 from 100 to 1.25 μm. Filled circles correspond to flux values, and the open circle represents a lower quality detection in the *IRAS* PSC catalog.

Comparison of Figure 1 with Figure 2 of Scarrott et al. (1991) reveals that an invisible near-infrared object is present in our image at the position where they predict the illuminator to be (about 3.″5 to the northwest of star 7). From our image we derive the position of the invisible object, relative to star 7, to be $\Delta\alpha = -2.''5 \pm 1.''0$, $\Delta\delta = 2.''0 \pm 1.''0$. These coincide with the position predicted by Scarrott et al. (1991, Fig. 2): $\Delta\alpha = -2''$, $\Delta\delta = 3''$, within the positional uncertainties. The position of the newly discovered source is consistent with it being the near-infrared counterpart of the *IRAS* point source IRAS 19433+2743.

Photometry of the source yielded an estimate of its near-infrared J, H, and K magnitudes: $m_K = 10.70$, $(J-K) = 3.90$, $(H-K) = 2.20$. Using the values of the *IRAS* fluxes for IRAS 19433+2743 together with the above near-infrared magnitudes, we obtained the broad-band spectral energy distribution (SED) of L810 IRS, presented in Figure 2. Using this figure, we estimate the bolometric luminosity of L810 IRS to be 890 $L_\odot$ for a distance of 2.5 kpc.

In the classification scheme of Lada & Wilking (1984) and Adams, Lada, & Shu (1987), young stellar objects with broad SEDs that rise steeply with increasing wavelength are "Class I" sources, i.e., protostars surrounded by infalling envelopes. Hence, Figure 2 indicates that L810 IRS is likely be a protostar.

3.2. *Near-Infrared Jet*

There is an interesting jetlike structure in the southwest corner of Figure 1. No similar feature is seen on the POSS plates or in the optical images of Neckel & Staude (1990) or Scarrott et al. (1991). Optical and infrared jets have been seen toward several other regions lodging embedded stars (e.g., Dopita, Schwartz, & Evans 1982; Mundt et al. 1984; Reipurth 1985).

The jet seems to point back toward the central regions of the nebula where L810 IRS is located, as shown in Figure 3. In this figure, the filled circles represent the positions of the two brightest K-band peaks along the jet, features B and C, which

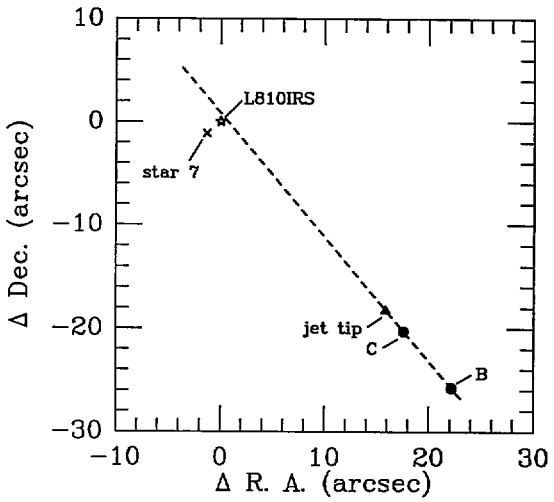

FIG. 3.—Spatial positions of the B and C peaks of the jet (*filled circles*) and of the northeastern tip of the jet (*filled triangle*). The infrared source L810 IRS (*star*) is almost collinear with these features of the jet. Star 7 (*cross*) is about 2″ away from the dashed line defined by the jet axis.

also appear in the *J*- and *H*-band images. The filled triangle represents the *K*-band position of the northeast tip of the jet. The dashed line in this figure represents a linear fit to the positions of these three points. L810 IRS is located less than 0.″5 away from the line. However, star 7 (*cross*) is about 2″ away from the line. The uncertainty in the location of the line is about 1″ at the positions of star 7 and L810 IRS. The collinearity of jet features B and C with L810 IRS strongly suggests that this source may also be responsible for the jetlike structure.

The jet is located approximately 35″ from L810 IRS. This corresponds to about 0.4 pc for a distance to the globule of 2.5 kpc (Xie & Goldsmith 1990). Furthermore, in the *K*-band, the jet has an extent of about 15″ (∼0.2 pc) and has an apparent opening angle of about 25° (jet tip to widest parts).

3.3. *Infrared Reflection Nebula*

Figure 1 shows that the infrared nebula extends about 20″ to the north and 20″ to the south of L810 IRS. The east-west width varies from about 16″ at the declination of L810 IRS to about 30″ near the top and bottom of the nebula. The nebula exhibits a north-south axis and wide lobes, features that also show in the L810 outflow map (Xie & Goldsmith 1990; Yun 1992). The symmetric shape of the infrared nebula suggests that the outflow axis may be close to being in the plane of the sky.

The location of the blue lobe southward of the illuminating source may explain the small extent of the optical nebula to the north of L810 IRS. The nebular light in the optical CCD maps is strongly asymmetric relative to star 7: the optical nebulosity is brightest to the south of star 7, whereas our infrared nebula is very symmetrically distributed north and south of L810 IRS. This could indicate that the blue outflow lobe has excavated a cavity toward the front edge of the cloud, explaining the presence of optical wavelength scattered light from the location of the blue lobe. Correspondingly, the red outflow lobe may have excavated a cavity toward the back of the cloud. As a result, most of the shorter wavelength radiation (optical, *J* band) scattered off the walls of this cavity would be absorbed within the L810 cloud. Thus, very little nebulosity would be seen in these wavelengths at the location of the outflow red lobe.

3.4. *Inclination Angle*

Even at the *K*-band wavelength, the nebula looks slightly asymmetric. A manifestation of the asymmetry is the displacement of L810 IRS below the line connecting the two points which define the narrowest part of the nebula. This asymmetry may be used to estimate the inclination angle of the nebular axis and presumably also the outflow axis. It is likely that the presence of the foreground half of an inclined circumstellar disk is responsible for obscuring the light reflected from the walls of the cavity located behind the central illuminating source. Such a structure would result in the apparent narrowing of the reflection nebula at the position of the disk. The positional offset of L810 IRS relative to the line connecting the two points which define the narrowest part of the nebula (this offset is measured to be ∼3″) was used to estimate the inclination angle of the disk and of the outflow axis to be about 11°, with an uncertainty of about 8°.

4. SUMMARY

We have obtained deep *J*, *H*, and *K* images toward L810 using the University of Arizona NICMOS 3 infrared array camera. We found a near-infrared source (L810 IRS) at the position where Scarrott et al. (1991) predicted the illuminator of the L810 nebula should be located. This stellar source is coincident with IRAS 19433+2743. The combined far- and near-infrared bolometric luminosity for this Class I protostar is about 980 $L_\odot$ (2.5 kpc distance). This luminosity could be produced by a 4 $M_\odot$ pre–main-sequence star, which may in the future ionize this nebula. L810 displays an extended near-infrared nebula which, in the *K* band, extends symmetrically to the north and the south of L810 IRS, exhibiting good spatial coincidence with the CO outflow lobes. The inclination angle of the nebular axis is estimated to be about 11° ± 8°, hence the nebular lobes are very close to being in the plane of the sky. A jetlike feature is also present in the vicinity of the nebula. This feature is particularly prominent at *K* and points back to L810 IRS, indicating that L810 IRS is likely to be a very active source.

This work has been partially supported by NSF AST 89-15606 and IRAS ADP grants to D. C. Support from JNICT to J. L. Y. in the form of a scholarship is gratefully acknowledged.

REFERENCES

Adams, F. C., Lada, C. J., & Shu, F. H. 1987, ApJ, 312, 788
Clemens, D. P., & Barvainis, R. E. 1988, ApJS, 68, 257
Dopita, M. A., Schwartz, R. D., & Evans, I. 1982, ApJ, 263, L73
Elias, J. H., Frogel, J. A., Matthews, K., & Neugebauer, G. 1982, AJ, 87, 7
Herbst, W., & Turner, D. G. 1976, PASP, 88, 308
Johnson, H. L., MacArthur, J. W., & Mitchell, R. E. 1968, ApJ, 152, 465
Lada, C. J., & Wilking, B. A. 1984, ApJ, 287, 610
Mundt, R., Buhrke, T., Fried, J. W., Neckel, T., Sarcander, M., & Stocke, J. 1984, A&A, 140, 17
Neckel, T., Chini, R., Gusten, R., & Wink, J. E. 1985, A&A, 153, 253
Neckel, T., & Staude, H. J. 1990, A&A, 231, 165
Reipurth, B. 1985, in ESO-IRAM-Onsala Workshop on (Sub-)Millimeter Astronomy, ed. P. Shaver & K. Kjär (Garching: ESO), 459
Rieke, M. J., Montgomery, E. F., Rieke, G. H., Vural, K., Blessinger, M., & Kleinhans, W. 1989, in Proc. Third Infrared Detector Technology Workshop, ed. C. R. McCreight (NASA TM-102209), 321
Scarrott, S. M., Rolph, C. D., & Tadhunter, C. N. 1991, MNRAS, 248, 27
Thompson, R., Rieke, M., Young, E., McCarthy, D., Rasche, R., Blessinger, M., Vural, K., & Kleinhans, W. 1989, in Proc. Third Infrared Detector Technology Workshop, ed. C. R. McCreight (NASA TM-102209), 331
Turner, D. G. 1986, A&A, 167, 157
Xie, T., & Goldsmith, P. F. 1990, ApJ, 359, 378
Yun, J. L. 1992, Ph.D. thesis, Boston Univ.
Yun, J. L., & Clemens, D. P. 1990, ApJ, 367, L73