THE ASTROPHYSICAL JOURNAL, 468:861–870, 1996 September 10

AN OUTBURST OF A DEEPLY EMBEDDED STAR IN SERPENS

KLAUS-WERNER HODAPP, JOSEPH L. HORA, AND JOHN T. RAYNER
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822; hodapp@ifa.hawaii.edu
ANDREW J. PICKLES
Institute for Astronomy, University of Hawaii, 1175 Manono Street, Building 393, Hilo, HI 96720; pickles@ifa.hawaii.edu
AND
E. F. LADD
Five College Radio Astronomy Observatory, University of Massachusetts, 619 Lederle Graduate Research Center, Amherst, MA 01003; ladd@gemini.phast.umass.edu
Received 1995 December 4; accepted 1996 April 4

ABSTRACT

We have discovered a substantial increase in the K-band brightness of a young, deeply embedded star in the Serpens NW star-forming region between 1994 August and 1995 July. The photometric history suggests a similarity to FUor or EXor outbursts. However, the star is more deeply embedded than any previous examples of those two types of eruptive events. Even in its bright state, the object is invisible in J, only scattered radiation is seen in H, the K band is still dominated by scattered light, and only in L' and longer wavelengths do we see a pointlike source. The Serpens Deeply Embedded Outburst Star (DEOS) has been detected at 800 μm, confirming its very young age. Its spectrum between 2.0 and 2.5 μm is a very steep, pure continuum, steeper than any published spectrum of a young embedded star. Most likely, the spectrum is thermal radiation from dust enshrouding the young star that completely veils any of the spectral features characterizing less obscured FUors and EXors stars. The outburst luminosity is only $\approx 15\ L_\odot$, so that the preoutburst luminosity must have been very low. The Serpens DEOS is probably a young star of very low mass.

Subject headings: infrared: stars — stars: pre–main-sequence — stars: variables: other (FU Orionis)

1. INTRODUCTION

Most young stars show small variations in brightness over time. In some rare cases, major outbursts have been observed. FU Orionis was the first young object where a major increase in brightness was observed, followed by a slow decrease over decades (Herbig 1977). Herbig (1989) defined two classes of such outbursts, distinguished by the duration of the outburst and the spectrum.

The light curves of FU Orionis stars (FUors) are characterized by a large increase in brightness, typically 5 mag in the optical, over times between 1 and 10 yr, followed by a slow decline in brightness over many decades. Their spectra are similar to the absorption spectra of F- or G-type supergiants at optical wavelengths, with pronounced P Cygni profiles at Hα, indicating absorption by outflowing material. The spectral classification is dependent on the wavelength of observations, with longer wavelengths indicating later spectral type. FUors show strong, cool stellar winds at velocities of several hundred km s^{-1} (Bastian & Mundt 1985). A strong Li I (λ670.7 nm) line indicates the presence of material not yet exposed to the high temperatures of a stellar interior (Herbig 1989).

The spectroscopic phenomena found in FU Orionis stars can be explained with a range of physical models. Petrov & Herbig (1992) made the point that the spectra can be explained by a single rotating star. Kenyon, Hartmann, & Hewett (1988) and Hartmann, Kenyon, & Hartigan (1991) interpret the spectrum in terms of activity in an accretion disk around a young star. This model has the advantage of including the FU Orionis phenomenon into the general picture of star formation, where the existence of some sort of accretion disk and the coupling of accretion and outflow phenomena have gained widespread acceptance.

EXor stars, the prototype being EX Lupi (Herbig 1977 and references therein), show outbursts of only slightly smaller magnitude, but shorter duration, than the FUors (Herbig 1989). The spectrum is even more distinct from that of FUors. EXors in maximum light show a spectrum dominated by emission lines in the optical and near-infrared, similar to a classical T Tauri star or a Herbig Ae/Be star.

All FUor and EXor stars are found in molecular clouds and usually can be identified with cool *IRAS* sources, confirming that they are associated with substantial amounts of cold dust and probably are very young stars. Submillimeter and millimeter emission has been found in some FU Orionis stars (Weintraub, Sandell, & Duncan 1989; Reipurth et al. 1993). In some of the best studied cases (i.e., for observational selection reasons, FUors of relatively low extinction), the stars are associated with ring-shaped nebulae that can be interpreted as one lobe of a bipolar nebula seen almost pole-on (Goodrich 1987). A few FUors with a more bipolar or cometary morphology have also been found, e.g., the FUor associated with HH 57 (Graham & Frogel 1985) and Parsamyan 21 (Staude & Neckel 1992), a cometary nebula identified spectroscopically and by its photometric evolution to be illuminated by a FUor.

In all cases reported so far, both the photometric and the spectroscopic identification of the FUor or EXor relied on optical techniques, usually photographic plates to establish the photometric history. There is no obvious physical reason why the instabilities in the disk accretion process thought to cause the outburst phenomena should be restricted to stars of sufficiently low extinction as to be optically visible. For all we know today, the evolution of a forming star from its main accretion phase (often called a class 0 phase, following André, Ward-Thompson, & Barsony 1993), through the phase of an infrared source (class I; Adams, Lada, & Shu 1987), to then becoming optically visible (class II) is smooth and accompanied by a gradual change in the star's photometric and spectroscopic properties. In young embedded clusters, we often find stars of different evolutionary classes in close vicinity. The (presumably) youngest of the stars detectable in the near-infrared in such clusters are characterized by a very steep near-infrared spectrum, the absence of a photospheric absorption-line spectrum, and maybe, but not necessarily, the presence of emission lines of molecular and atomic hydrogen (Hodapp & Deane 1993).

In this paper, we report on the discovery and basic characterization of a deeply embedded star in the Serpens NW star-forming region that has undergone a substantial increase in brightness in less than 1 yr. While this photometric behavior certainly suggests a similarity to a FUor or EXor event, the *K*-band spectrum is a featureless, very steep continuum, unlike the spectra of either FUors or EXors. In the following, we will refer to this object as a Deeply Embedded Outburst Star (DEOS).

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Imaging Photometry*

In 1991 August, a wide-field mosaic of the whole Serpens molecular cloud (Fig. 1) was obtained in *K*′ at the University of Hawaii (UH) 2.2 m telescope using the UH infrared camera (Hodapp, Rayner, & Irwin 1992).

Deeper preoutburst data in *H* and *K*, detecting the DEOS in what we assume to be its quiescent state, were obtained with the new infrared camera QUIRC (Hodapp et al. 1995) on 1994 August 16–18 at the UH 2.2 m telescope f/10 focus (Fig. 2). This new infrared camera is equipped with a HAWAII 1024 × 1024 HgCdTe detector array manufactured by the Rockwell International Science Center (Kozlowski et al. 1994). The image scale in QUIRC is 0.″183 pixel^{-1}, and the total field of view is $\approx 3' \times 3'$.

With the same instrumentation, Hodapp (1995) discovered the increased brightness of the star and its associated nebula on 1995 July 12 UT (Table 1). Deeper images were obtained in the following two nights (Fig. 3).

A high-resolution *K*-band image of the Serpens DEOS was obtained on 1995 July 19 UT, with the UH 2.2 m telescope f/31 fast tip-tilt secondary mirror and QUIRC. The pixel scale was 60 mas pixel^{-1}. During each of the nine 60 s exposures, the target was fast-guided by measuring optical light centroids from a guide star 5′ away at 80 Hz with a fast Tek 512 CCD and by using that information to drive the Physik Instrumente piezo-driven fast-guide platform that supports the f/31 secondary mirror. This system corrects for telescope motion during exposures and permits some correction of atmospheric image motion. The high-resolution image was used to determine the radial intensity

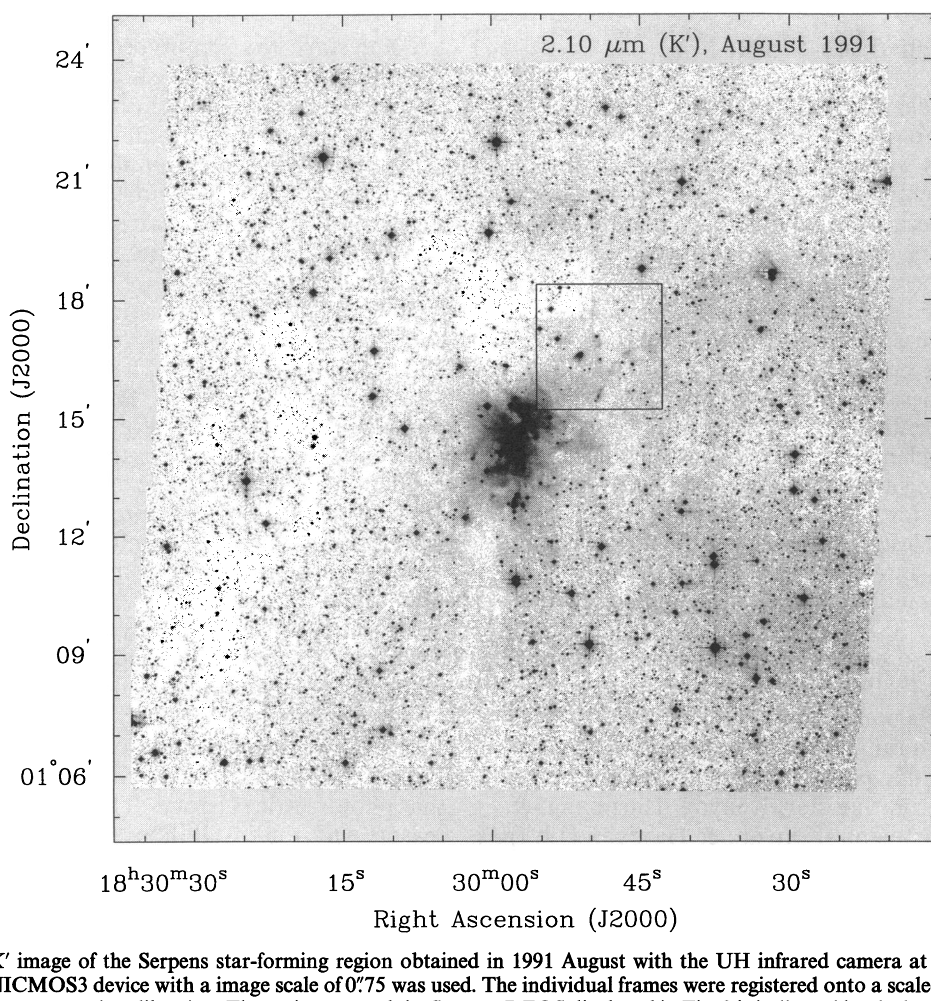

FIG. 1.—Wide-field *K*′ image of the Serpens star-forming region obtained in 1991 August with the UH infrared camera at the f/10 focus of the 2.2 m telescope. A 256 × 256 NICMOS3 device with a image scale of 0.″75 was used. The individual frames were registered onto a scaled *I*-band CCD frame of the region to ensure a reliable astrometric calibration. The region around the Serpens DEOS displayed in Fig. 2 is indicated by the box.

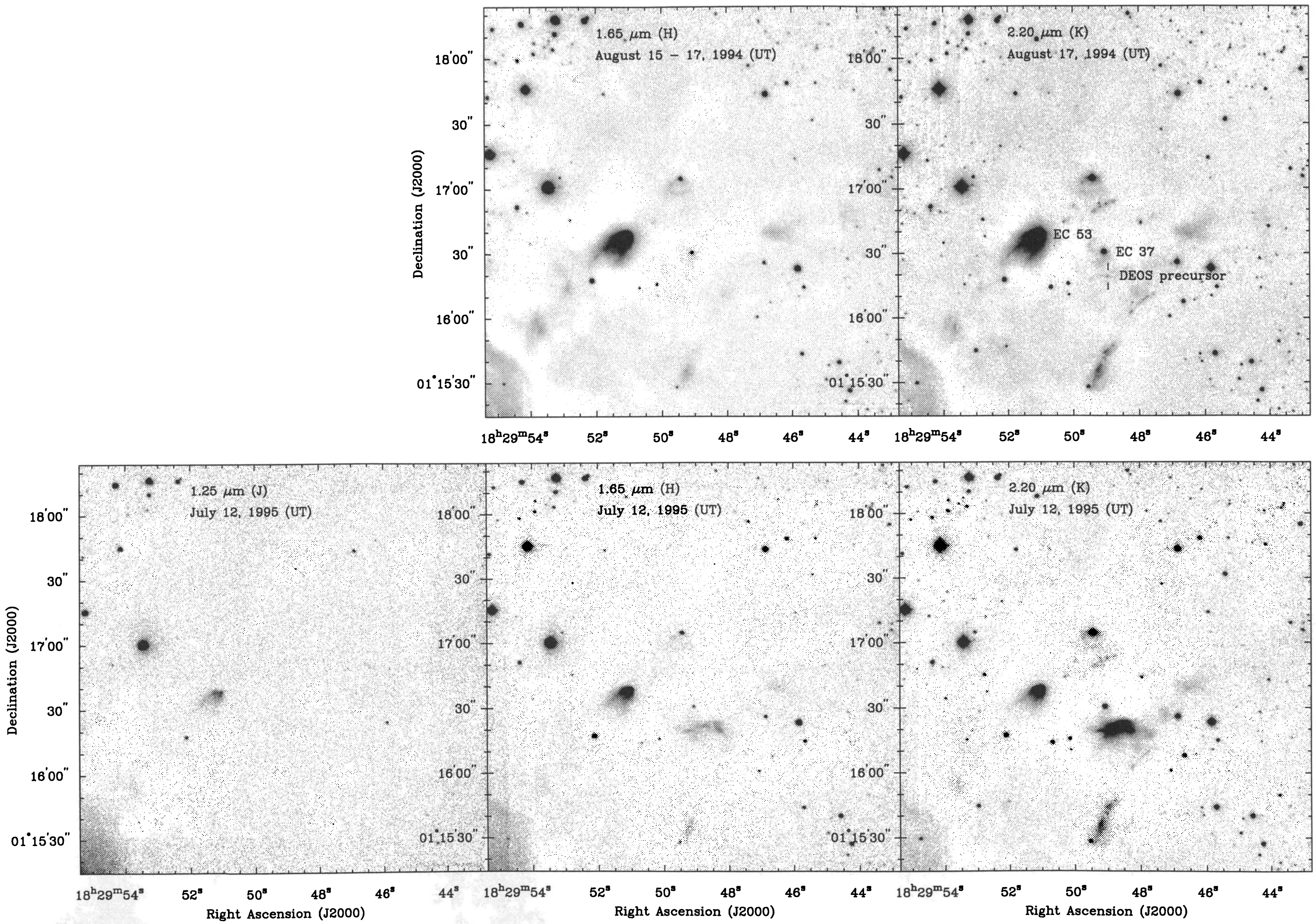

FIG. 2.—The images on the top were taken on 1994 August 17 with QUIRC at the UH 2.2 m telescope. Stars in the 1994 *K*-band frame are labeled for reference to Table 1. The position of the DEOS precursor is in the middle of the two vertical marks and is labeled. On the bottom are *K*-, *H*-, and *J*-band images taken in 1995 July 12 with the same instrumentation. The DEOS is near the center of the images. In 1995, it appears bright in *K*, very faint in *H*, and is invisible in *J*.

TABLE 1

NEAR-INFRARED PHOTOMETRIC DATA OF NEWLY FOUND VARIABLE SOURCES IN SERPENS

Band	1988–1989	1991 August	1994 August	1995 July	1995 October	1996 February
			EC 53			
H	12.2	12.9	11.7	13.1	14.1	...
K′	...	11.4	...	12.1	...	...
K	10.5	...	10.2	11.6	12.0	10.2
			Serpens DEOS			
H	...	...	...	15.0	...	...
K′	...	...	...	12.2	...	...
K	...	...	16.1	11.5	11.4	11.8
			EC 37			
H	...	16.3	16.6	17.1	17.3	...
K′	...	13.5	...	14.2	...	...
K	13.0	...	13.2	13.5	13.6	13.3

TABLE 2

NEAR AND MID-INFRARED PHOTOMETRY OF THE SERPENS DEOS IN 1995

λ (μm)	Magnitude
1.6	15.0
2.1	12.2
2.2	11.4
3.8	6.9
4.8	5.2
11.7	1.6
20.6	−0.3

profile of the central condensation of the nebula associated with the DEOS (Fig. 4).

On 1995 August 16, NSFCAM (Shure et al. 1994) at the IRTF[1] was used to obtain photometrically calibrated images in the *K*, *L′* (Fig. 3), and *M* bands at a pixel scale of 0″.15 pixel^{-1} (Table 2).

The MIRAC2 mid-infrared camera (Hoffmann et al. 1993) was used at the IRTF on 1995 October 11 to obtain photometry of the Serpens DEOS at 11.7 and 20.6 μm (Table 2). For the 11.7 μm observations, a series of 15 exposures with 10 s on-source time were taken with telescope offsets of a few arcseconds between each integration. We were chopping at 2 Hz and also nodding the telescope completely off-source and taking another chop pair. These four beams (total of 40 s) were combined for each 10 s on-source image. The standard star γ Aql was observed in the same way, and its flux at 11.7 μm was assumed to be 78.4 Jy. At 20.6 μm, a series of 13 exposures with 10 s on-source time were taken. The standard star used for the 20.6 μm observations was β Peg, with an assumed flux of 95.3 Jy.

The brightness of the DEOS was monitored on 1995 October 12 UT in *H* and *K* with QUIRC at the f/10 focus of the UH 2.2 m telescope and on 1996 February 6 in *K*, using an upgraded version of QUIRC (Hodapp et al. 1996).

Photometry in *J*, *H*, *K′*, and *K* was calibrated using the faint standard stars published by the United Kingdom Infrared Telescope (UKIRT). Relative photometry, i.e., the change in magnitude, is based on a system of stars in the field of view that show no signs of variability (Table 3). One star (EC 38) not included in Table 3 was also checked for variability but was found to be constant. Photometry with NSFCAM was calibrated against the standard stars of Elias et al. (1982).

Astrometry was obtained using the large *K′* mosaic obtained in 1991. To avoid distortions of the astrometric grid in the alignment process of the individual frames, five *I*-band images were obtained with a 2048 × 2048 Tektronix CCD at the f/10 focus of the UH 2.2 m telescope. The center frame had sufficient overlap with the four corner frames that precise alignment of those frames was possible. The combined *I*-band frame was then scaled to match the plate-scale of the UH infrared camera and used to register the individual 256 × 256 *K′* frames onto the correct position. The resulting wide-field *K′* image (Fig. 1) is therefore expected to have less than 1″ of systematic distortion of the astrometric grid as a result of the alignment process. The wide-field *K′* image contains seven *Hubble Space Telescope* Guide Star Catalog stars that were clearly identifiable, unsaturated, apparently single stars. Astrometry on the wide-field image is based on these stars; astrometry in the deep images (Figs. 2 and 3) is based on a set of secondary reference stars in Figure 1. The newly found Serpens DEOS has coordinates $18^h29^m49^s.10$ $+01°16''20''.6$ (J2000).

2.2. *Infrared Spectroscopy*

The first *K*-band spectrum of the Serpens DEOS and its associated nebulosity was obtained on 1995 July 14 by G. Wright using CGS4 on UKIRT. This spectrum showed that

TABLE 3

REFERENCE STAR *H*, *K′*, AND *K* PHOTOMETRY

Star	R.A. (2000)	Decl. (2000)	*H*	*K′*	*K*
R1	18 29 52.1	+01 16 18	15.02	13.91	13.71
R2	18 29 51.7	+01 17 44	17.52	15.06	14.77
R3	18 29 45.4	+01 17 32	18.05	14.44	14.09
R4	18 29 45.9	+01 17 14	18.37	15.60	15.30
R5	18 29 46.8	+01 17 44	14.25	12.84	12.67
R5	18 29 54.4	+01 16 52	15.65	14.19	13.99

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The *H*- and *K*-band photometry of the reference stars was obtained in 1994 August 17 from our deepest images. The *K′* photometry was obtained in 1995 July 12.

[1] The Infrared Telescope Facility is operated by the University of Hawaii under contract with the National Aeronautics and Space Administration.

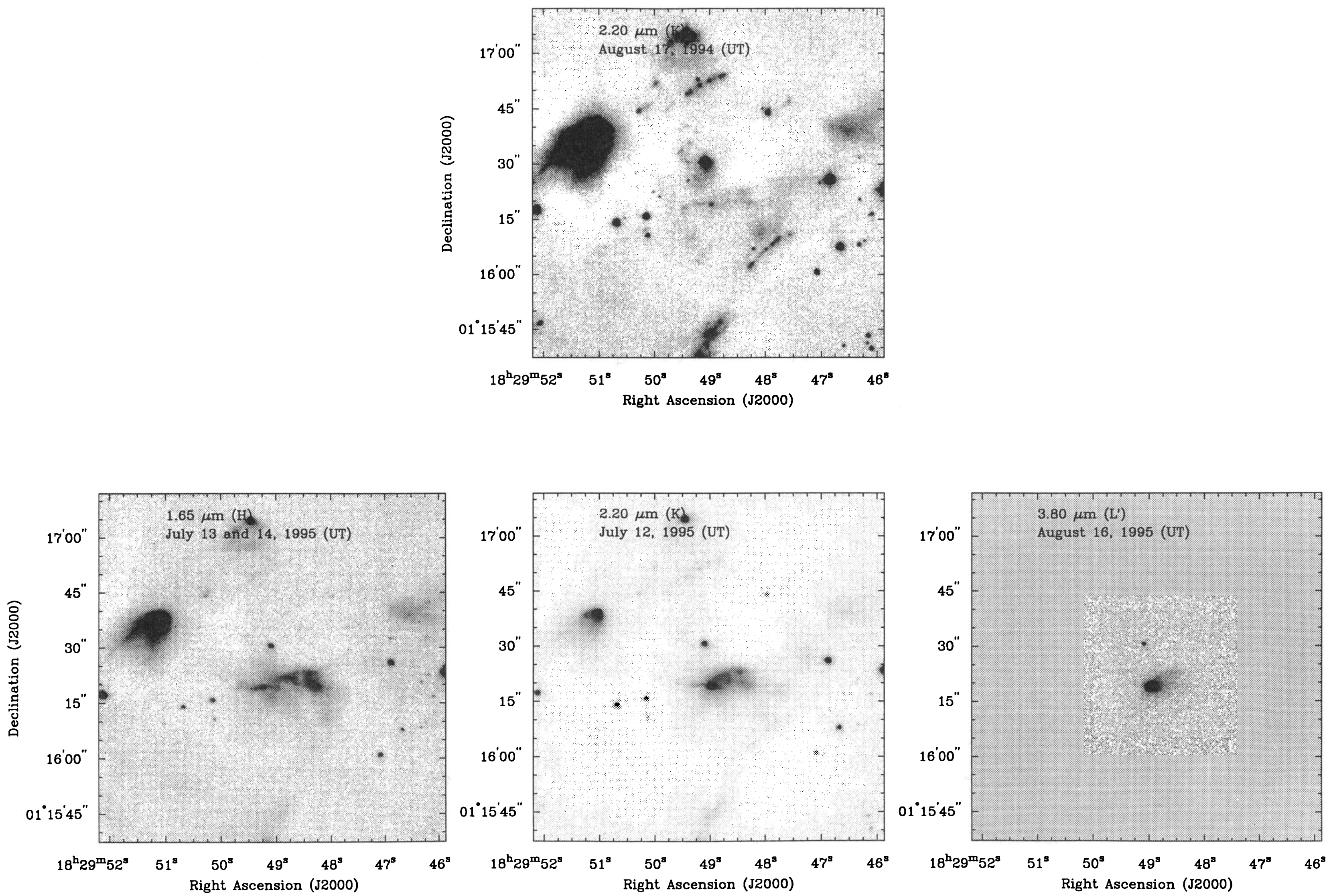

FIG. 3.—The area of the newly discovered DEOS and objects EC 37, EC 38, and EC 53. The lower panels are images in *H*, *K*, and *L'* taken in 1995 July and August. The top center panel is a deep *K*-band image obtained in 1994 August, showing the nebula associated with the DEOS in the preoutburst state.

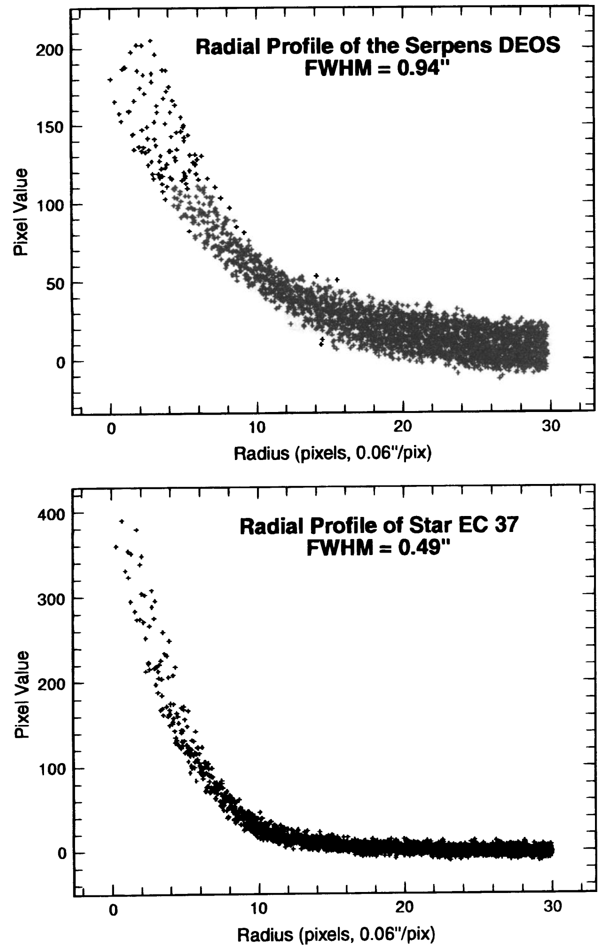

FIG. 4.—Radial profiles in K of the Serpens DEOS, based on a tip-tilt-corrected image taken at the UH 2.2 m telescope in 1995 July 19 UT.

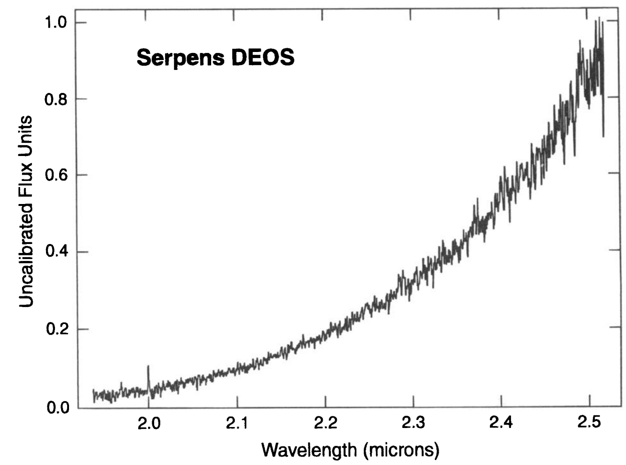

FIG. 5.—K-band spectrum of the Serpens DEOS obtained with KSPEC at the f/31 focus of the UH 2.2 m telescope. The spectrum is in relative flux units but not absolutely calibrated.

the combined spectrum of the central condensation and some of the surrounding nebulosity was a steep continuum in the K band.

Another infrared spectrum (Fig. 5) of the new DEOS in Serpens was obtained on the nights of 1995 September 4 and 6 UT using the upgraded KSPEC spectrograph (Hodapp et al. 1996). This cross-dispersed spectrograph obtains a spectrum from 0.9 to 2.5 μm in a single exposure on a HAWAII 1024 × 1024 detector array. The slit was 0".6 wide and 15" long for the observations reported here. Using the slit-viewing camera of KSPEC, the slit was positioned to include the K-band flux maximum of the central condensation. A total of 80 minutes of integration time on the bright central condensation of the Serpens DEOS was

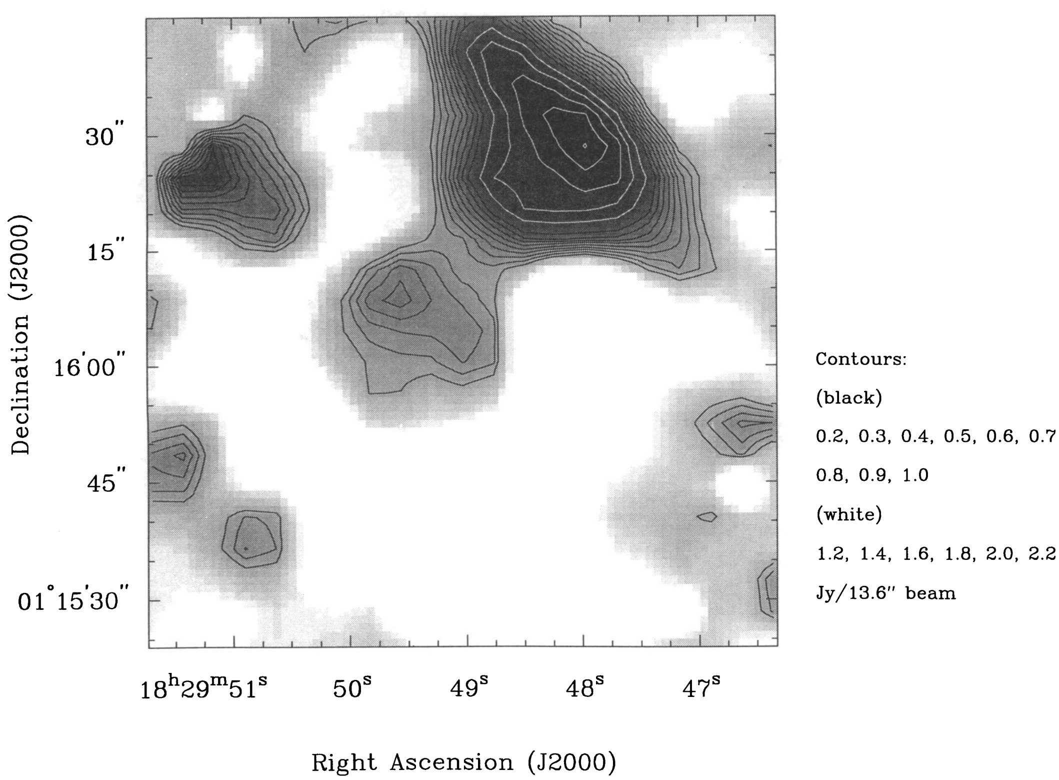

FIG. 6.—Map of the 800 μm emission in the area of the Serpens DEOS taken with UKT14 at the JCMT telescope with a beam size of 13".6. The bright source in the northwest of the map is S68 N, the newly found DEOS is near the center of the map, while EC 53 is in the northeast.

obtained. For atmospheric absorption correction, bright stars of early spectral type (A0 and A5) close on the sky to the Serpens star-forming region were observed. The Brγ line in the spectra of those stars was removed by interpolating the continuum adjacent to that line in the spectrum of the stars prior to using those spectra to correct for atmospheric absorption in the object spectra. To obtain a spectrum in relative flux units, the reduced spectrum was multiplied by a Planck function of $T = 9000$ K, a temperature between the effective temperatures of the atmospheric absorption standards used.

2.3. *Mapping at* 800 μm

The submillimeter continuum emission from the Serpens DEOS was mapped (Fig. 6) with the James Clerk Maxwell Telescope (JCMT)[2] on Mauna Kea, Hawaii. The observations were taken 1995 September 28 with the facility UKT-14 bolometer system and the standard 800 μm broadband filter. Four maps covering ~80″ × 80″ centered on the 2 μm source position were constructed by rapidly scanning the photometer across the region while synchronously chopping the secondary with a throw of 32″. The telescope was slewed in azimuth at a rate of 4″ s^{-1}, and data were taken in 1 s intervals, yielding highly oversampled maps with 4″ pixels. These raster-scanned data sets were reduced with the NOD2 package (Haslam 1974) as modified for use at the JCMT. The data were calibrated against Uranus and the secondary standards G34.3 and N7538 IR1 (Sandell 1994). The beam size (FWHM = 13″.6 ± 0″.6) and shape (circular to 5% of peak flux) were determined from maps made of Uranus on the same night.

Flux was found at the positions of both the DEOS and EC 53, indicating that both are indeed deeply embedded young stars surrounded by substantial quantities of warm dust. The 800 μm image of the DEOS appears nearly pointlike, with an integrated flux of 0.6 ± 0.1 Jy.

3. RESULTS AND DISCUSSION

3.1. *Photometry*

The *K*-band photometry in our 1994 image, as well as the upper limits given by the nondetection of that star in 1991 (Fig. 1), and on the image taken in 1988 and 1989 by Eiroa & Casali (1992) do not indicate any periodic variability of substantial amplitude. The nebula associated with the precursor of the DEOS was faintly visible in the *K* band in 1994 (Fig. 3) and shows basically the same morphology as the nebula after its brightening in 1995.

During observations of the Serpens region at UKIRT, Casali (1995) obtained a frame that ended only 2″ away from the position of the DEOS. He reports seeing an indication of the reflection nebulosity associated with the DEOS on that frame. While precise photometry is not possible, this observation indicates that the Serpens DEOS was already bright on 1995 May 1. This gives an upper limit to the rise time of the DEOS outburst of 8.5 months.

When discovered on 1995 July 12 UT, the Serpens DEOS appeared 4.6 mag (in *K*) brighter than in 1994 (Table 1). We assume that the brightness observed on 1994 August was the preoutburst quiescent state. At the brightness observed in 1994, the object would have been invisible in the 1991 image, as was indeed observed. This amplitude of 4.6 mag in the near-infrared matches the typical amplitudes of FUors quite well, with the caveat that most historic FUors have been found and monitored in the optical, and the precursor magnitudes are usually obtained from photographic plates. EXors usually have similar amplitudes in the optical, but the *K*-band amplitude of the embedded EXor SVS 13 (Eislöffel et al. 1991; Liseau, Lorenzetti, & Molinari 1992; Aspin & Sandell 1994) was smaller.

The infrared photometric data obtained between 1995 July and 1996 February are summarized in Table 2. At 800 μm, a flux of 0.6 Jy was measured at the position of the Serpens DEOS.

3.2. *Morphology*

The nebula associated with the Serpens DEOS is of bipolar morphology, with the western lobe more extended and brighter than the eastern one (Fig. 3). In the *H* band, there is no detectable central condensation, and the image is dominated by the lobes of the bipolar nebula. In addition, we note some very faint extended emission oriented in the equatorial plane (north-south) of the bipolar nebula, i.e., oriented perpendicular to the axis of the bipolar lobes. This is most likely scattered radiation, probably backscattered light from the lobes scattering again on the outer surface of an extended oblate structure surrounding the central star. Gaseous structures of similar morphology and dimensions (≈3000 AU) have been found to be rotating disks by Sargent & Beckwith (1987).

In *K*, a central condensation is visible. This condensation has a broader profile than stars, however, so it is not a direct image of the central star (Fig. 4). A tip-tilt–corrected *K*-band image shows the FWHM of stars to be 8.0 ± 0.2 pixel (0″.49), while the central condensation in the DEOS nebula has FWHM = 15.7 pixel (0″.94). Based on the morphology, we think this central condensation is multiply forward-scattered light from the central star. In the *L*′ band, the DEOS is unresolved and surrounded by nebulosity of similar morphology to that observed in the *K* band. In the *M*′ band and at longer wavelengths, the DEOS is unresolved and the nebulosity is undetectable in our image. At 11.7 and 20.6 μm, the DEOS appears pointlike, and, in a field of 30″ × 30″, we did not find any other point source or extended emission down to limiting flux levels of 0.15 Jy $arcsec^{-2}$ at 11.74 μm and 1.4 Jy $arcsec^{-2}$ at 20.6 μm.

Based on photometry and the morphology of the nebula in the 1994 *K*-band image, we conclude that the precursor of the Serpens DEOS appeared like a typical faint, deeply embedded young star with a bipolar nebula seen nearly edge-on. Stars of the FUor and EXor type are usually associated with nebulosity and are found near star-forming regions. There seems to be a continuum in the degree of embeddedness and in the extinction of confirmed FUors. Furthermore, being discovered by optical techniques, the list of currently known FUors and EXors must be heavily biased toward objects of low extinction and/or favorable disk orientation. We conclude that, morphologically, the Serpens DEOS appears more deeply embedded than the previously known classes of young outburst stars, but it appears related to those other classes.

3.3. *Spectroscopy*

Only wavelengths longer than the *H* band show detectable flux from the central condensation of the nebula associ-

[2] The James Clerk Maxwell Telescope is operated by the Royal Observatories on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.

ated with the Serpens DEOS. The *K*-band spectrum (Fig. 5) does not show any features other than small artifacts from poor sky subtraction, atmospheric correction, and bad pixels. In particular, a spike in the spectrum at 2.000 μm is most likely not an emission line but the result of higher noise at that wavelength due to an OH airglow line, amplified by the division by the standard star spectrum that has a deep absorption feature around this wavelength. The spectrum appears as a very steep, smooth continuum rising almost exponentially throughout the *K* band. The flux ratio between 2.0 and 2.5 μm is about 20, and the *K*-band spectrum can roughly be described by a power law with exponent 13.4, without implying any physical model for this.

We do not see any indication of S(1) 1–0 line emission at 2.12 μm or Brγ emission at 2.17 μm frequently observed in very young stars, nor do we detect the CO band heads longward of 2.29 μm in either absorption or emission. There is no obvious effect from water absorption at 1.9 μm in the spectrum, but such a broad feature would be hard to detect in a steep continuum spectrum with detectable flux levels only at the long-wavelength side of the absorption feature.

The spectrum is certainly different from the absorption-line spectrum usually found in FUors at near-infrared wavelengths, or from the emission-line spectrum found in EXors. The *K*-band spectrum of FU Orionis itself shows strong CO band head absorption (Hartmann & Kenyon 1987). The infrared spectrum of L1551 IRS 5 (Mundt et al. 1985; Carr, Harvey, & Lester 1987) and Z CMa (Hartmann et al. 1989), suspected FUors based on their optical spectra, show faint emission lines of atomic and molecular hydrogen, but are otherwise characterized by the absorption bands of CO longward of 2.29 μm and the Ca I blend at 2.263 μm in absorption. Similarly, unpublished KSPEC spectra (Greene 1995) of RNO 1B, RNO 1C, Elias 1–12, and L1551 IRS 5 in the 1.0–2.5 μm range all show strong CO band head absorption, marked broad H_2O absorption centered at 1.9 μm, and other absorption features. The infrared spectrum of the EXor SVS 13 (Eislöffel et al. 1991) showed the CO band heads at 2.29 and 2.32 μm in emission.

Steep continuum spectra like the one observed in the Serpens DEOS have been found in spectral surveys of embedded young clusters of stars, e.g., by Hodapp & Deane (1993) in L1641 North. In such young clusters, one typically finds stars with classifiable absorption spectra, stars with emission lines, and stars with near-featureless steep continuum spectra. From the discovery statistics, it is clear that FUor outbursts must be repetitive (Herbig 1977), and, for EXors, this has actually been observed. In a young cluster of stars, therefore, one would expect, over timescales of 10^5 yr, almost all stars to undergo one or several outbursts. Outbursts of the less embedded stars with absorption or emission spectra can be expected to have the characteristics of FUors or EXors. If a similar outburst occurred in one of the deeply embedded stars with a steep continuum spectrum, one would expect an event with the observational characteristics of the DEOS found in Serpens.

The extreme steepness of the spectrum, and the association of the star with a bipolar nebula seen nearly edge-on, strongly suggests that the Serpens DEOS is in the early class I phase of its evolution. However, the dust distribution geometry of the Serpens DEOS is not sufficiently understood to derive a unique model for this object. The continuum spectrum of low color temperature suggests that this spectrum is dominated by the emission of warm dust. This dust may be spatially separated from the accretion disk and may just reprocess radiation from the disk into the near-infrared continuum. A difficulty with this model is that, in similarly embedded FUors, e.g., L1551 IRS 5, light from the disk is being scattered to the observer and shows the characteristic absorption spectrum. An alternative is to assume that the disk itself is emitting a continuous spectrum, within the limits set by the observations. We note that the slope of the *K*-band spectrum corresponds to a color temperature below 400 K. Absorption will certainly affect the spectrum, so this value must be taken as a lower limit to the disk temperature. Still, the low color temperature suggests that the disk pseudophotosphere may be well within the temperature range where dust particles survive. The dust could thus provide substantial continuum opacity within the disk itself, veiling all or most absorption or emission features.

3.4. *Submillimeter Emission and Spectral Energy Distribution*

Our 800 μm map has higher resolution than a 1100 μm map by Casali, Eiroa, & Duncan (1993), also obtained at the JCMT. Common to both maps is the detection of flux from EC 53 and the strong extended emission associated with S68 N (McMullin et al. 1994) about 30″ north and west of the position of the DEOS. On the map of Casali et al. (1993), the position of the DEOS is on a ridge of flux connecting that emission region with the flux associated with FIRS1. Contrary to that, we find that, at 800 μm and with the DEOS in its bright state, there is a localized maximum of flux near the position of the DEOS. Their 1100 μm map is low in spatial resolution and signal-to-noise, however, so we cannot conclude with any certainty that the submillimeter flux from the DEOS was absent at the epoch (1990 May) of their observations. The 3.1 mm continuum map and CS $J = 2$–1 map of McMullin et al. (1994) does not show any emission at the position of the DEOS.

The 800 μm flux maximum near the DEOS is slightly extended in the northeast-southwest direction, and the flux peaks 9″ northeast of the DEOS position. This extension and the shift in peak position are not significant, however, and given that we have not detected any additional sources at 11.7 and 20.6 μm near the DEOS, we attribute all the 800 μm flux to it. At its position, an integrated flux of 0.6 Jy is measured, giving $\nu F_\nu = 2.25 \times 10^{-15}$ W m^{-2}.

The measured points of the spectral energy distribution (SED) are shown in Figure 7. For lack of current, high spatial resolution, far-infrared observations, we have no data points in the spectral regions where the SEDs of young embedded stars tend to peak.

As is common in very young stars, the spectrum is broader than can be fitted with a single graybody spectrum. For comparison, we have plotted the SED of L1551 IRS 5 (the prototypical bipolar outflow source), a typical class I source that has also been listed as a FUor based on its optical spectrum (Mundt et al. 1985). For Figure 7, we have scaled the photometric data points for L1551 IRS 5 ($d = 140$ pc; Elias 1978) to the distance of the Serpens DEOS ($d = 311$ pc; de Lara, Chavarria-K., & López-Molina 1991).

Calculating the luminosity of the Serpens DEOS is highly uncertain because of the lack of far-infrared data. By interpolating the scaled SED of L1551 IRS 5 to our 20 and 800 μm data points, we get a very rough estimate of 15 $L_\odot$ for the luminosity of the DEOS in the 1995 July–September

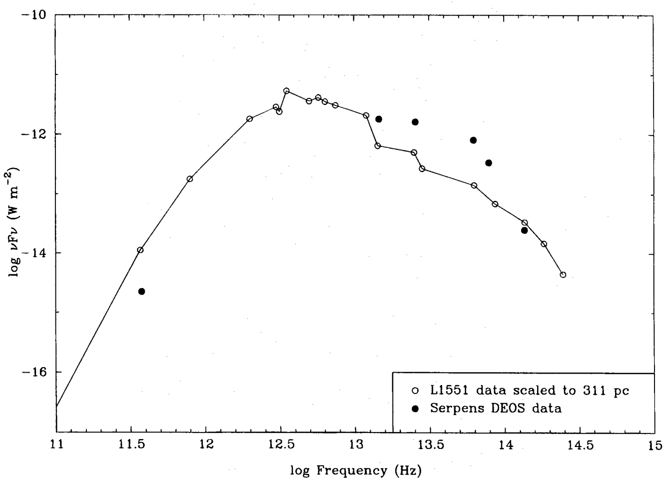

FIG. 7.—SED of the Serpens DEOS. For comparison, the SED of L1551 IRS 5, scaled to the distance of Serpens, is included.

period. The Serpens DEOS has higher mid-IR fluxes but weaker 800 μm emission than L1551 IRS 5, making the spectrum "warmer" overall. However, the near-infrared part of the spectrum is steeper than that of L1551 IRS 5, most likely due to a more edge-on orientation of the dense disk surrounding the star, more dust in the path of the light even in the polar direction of the bipolar nebula, and possibly a lower disk temperature. It is possible that the Serpens DEOS has yet to carve out as large an outflow cavity as the one associated with L1551 IRS 5 that allows optical and near-infrared radiation from the disk pseudophotosphere to escape and be scattered toward the observer. A luminosity of 15 $L_\odot$ is below the luminosity of L1551 IRS 5 (30 $L_\odot$; Cohen et al. 1984) and well below that of the classic FUors FU Orionis (250 $L_\odot$) and V1057 Cyg (470 $L_\odot$) (Cohen, Dopita, & Schwartz 1986).

A possible partial explanation for the low 800 μm flux may be that the dust responsible for that emission has not yet reached its new equilibrium temperature after the outburst of the DEOS. Also, Ladd et al. (1995) found that part of the submillimeter flux from L1551 IRS 5 comes from the walls of the outflow cavity and may be dynamically heated, involving a still longer timescale to reach the higher temperatures. However, the effects listed here are not likely to explain the order-of-magnitude difference in the 800 μm fluxes between the two objects compared here. We have to conclude, therefore, that the Serpens DEOS is surrounded by a smaller mass of cold dust than L1551 IRS 5. Within the limitations imposed by the available data, the SED appears consistent with that of a class I source, indicating that the DEOS is indeed in a very early evolutionary phase.

The Serpens DEOS in its preoutburst state must have been an object of very low luminosity. Under the assumption that the bolometric luminosity changed proportional to the K-band flux, the preoutburst luminosity of the DEOS was 0.22 $L_\odot$. This assumption seems reasonable but is probably not exactly true, since the outburst may evaporate some dust particles and change the dust distribution in the immediate vicinity of the star. This low estimate is consistent with the upper limit of 8 $L_\odot$ for the bolometric preoutburst luminosity, derived by Hurt & Barsony (1996) from the *IRAS* flux levels in this confused region, after HIRES processing of the data.

From this luminosity value, some constraints on the mass can be derived. D'Antona & Mazzitelli (1994) have computed evolutionary tracks for pre–main-sequence stars, modeled as contracting gas spheres, excluding accretion luminosity. The Serpens DEOS, based on its morphology and spectrum, is a deeply embedded class I object, and we assume its age to be 10^5 yr. The 10^5 yr isochrones of any of these models intersect the 0.22 $L_\odot$ line near the locus of $\approx$0.1 $M_\odot$ stars. Since our luminosity value includes accretion effects while the model tracks exclude it, this is actually an upper limit to the mass.

Given the observational limitations imposed by the lack of far-infrared data, the potential problems in scaling bolometric luminosity by the K-band outburst amplitude, and the difficulties in comparing with evolutionary tracks computed under highly idealized physical conditions (no accretion), the only claim that we can make with any confidence is that the Serpens DEOS is a very low mass young star.

3.5. *The Nebula EC 53*

To the east of the newly found DEOS, at $18^h29^m51^s.04$ $+01°16'38''.7$ (J2000), lies the parabola-shaped nebula listed as EC 53 by Eiroa & Casali (1992). Our observations also show that EC 53 changes its brightness substantially on a timescale of 1 yr (Table 1). Between 1988 and 1994, the brightness has varied by about 1 mag. Starting in 1994, the nebula has faded by 1.4 mag but has recently returned to its brighter state. EC 53 is a nebula of cometary morphology, most likely the visible half of a bipolar nebula inclined against the line of sight. The object appears extended at wavelengths up to 2.5 μm and does not contain a starlike condensation.

A similar object with a documented history of photometric variability in the infrared is SVS 13, the driving source of the HH 7-11 system of Herbig-Haro objects in NGC 1333. This object was found to vary over 3 mag at optical wavelengths and about 1 mag in the near-infrared on timescales of 1 yr or more by Eislöffel et al. (1991), Liseau et al. (1992), and Aspin & Sandell (1994). Both the timescale and the typical amplitude are similar to the variability observed in EC 53. The small number of data points for EC 53 do not allow a classification of the type of variable star illuminating the nebula. The very young age suggested by the morphology of the nebula and the fact that such objects are thought to be dominated by accretion luminosity makes it likely that relatively minor instabilities in the disk accretion are the cause of the variability.

3.6. *Another Variable Star (EC 37)*

The star EC 37 (Eiroa & Casali 1992), at $18^h29^m49^s.10$ $+01°16'30''.6$ (J2000), just north of the Serpens DEOS, was also found to vary on timescales of several years as shown in Table 1. Eiroa & Casali give a K magnitude of 13.2 for this star, but there is a systematic difference of 0.2 mag between our photometry of constant stars in the field and theirs, so that, by recalibrating their photometry to the constant stars used by us (to the extent that they were included in their list), the brightness of EC 37 in 1988 must have been 13.0 mag, consistent with the slow decrease in brightness over several years observed by us.

EC 37 is associated with nebulosity (Fig. 3) of much lower surface brightness than EC 53 and the DEOS, is less deeply embedded, appears starlike, and does not emit significant 800 μm flux. It is probably more evolved than the DEOS or EC 53. Projected against dense parts of the Serpens NW molecular cloud, it is unlikely to be a background star. Most likely, it is an embedded T Tauri star, for which variability is very common. The long timescale and substantial amplitude of the brightness change suggest a similar drop in disk accretion rate and an associated drop in accretion luminosity to that discussed for the younger object EC 53.

It should be noted that, in their original infrared survey of the Serpens molecular cloud, Strom, Vrba, & Strom (1976) already reported the variability of source SVS 20 with a K-magnitude change of 1.5 mag between 1974 and 1975, and an L-magnitude change of 1.8 mag in the same period. This shows that the Serpens molecular cloud contains several objects young enough to show substantial variability.

4. CONCLUSIONS

Our photometric data at near-infrared, mid-infrared, and submillimeter wavelengths show that the newly discovered object in Serpens is a deeply embedded star that shows all the characteristics of a very young object of class I SED type. The K-band spectrum is a featureless, very steep continuum similar to those found in other extremely young sources in embedded clusters, but more extreme in its steepness. While the photometric history of this object clearly links it to the two established classes of young stars with brightness outbursts, FUors and EXors, it is distinct from either of those two classes in that it lacks the characteristic absorption spectrum of FUors or the emission lines of EXors.

Contrary to many optical FUors of relatively low extinction, the nebula associated with the Serpens DEOS appears as a bipolar nebula with its equatorial disk seen very nearly edge-on. Despite the uncertainty introduced by the geometry of the object, the lack of absorption lines seen in the scattered light (dominating the K band) indicates larger quantities of warm dust around this object than is usual for FUors and EXors. Possibly, parts of the disk are cool enough for dust particles to survive and contribute to the continuum spectrum. The Serpens DEOS is likely the most deeply embedded and, presumably, one of the youngest stars found so far to undergo an outburst in brightness. It is also an object of relatively low luminosity and probably of very low mass.

The photometric behavior of the Serpens DEOS strongly suggests that the disk accretion instabilities that form the basis for the FUor and EXor phenomena also occur in even more deeply embedded stars and are not only a phenomenon found in the later T Tauri phase.

We thank Lynne Deutsch and Mrinal Iyengar for obtaining the MIRAC data for us, and William Hoffmann and Giovanni Fazio for making this superb camera available for this project. Gillian Wright obtained the first K-band spectrum of the Serpens FU Orionis with CGS4 on UKIRT, giving the first indication of the continuum nature of the spectrum. We thank T. Greene, G. Herbig, and A. Tokunaga for helpful discussions. We are indebted to the referee, R. Mundt, for his helpful comments and suggestions. Astronomy research at the Five College Radio Astronomy Observatory is supported by the National Science Foundation under grant AST 94-20159.

REFERENCES

Adams, F. C., Lada, C. J., & Shu, F. H. 1987, ApJ, 312, 788
André, Ph., Ward-Thompson, D., & Barsony, M. 1993, ApJ, 406, 122
Aspin, C., & Sandell, G. 1994, A&A, 288, 803
Bastian, U., & Mundt, R. 1985, A&A, 144, 57
Carr, J. S., Harvey, P. M., & Lester, D. F. 1987, ApJ, 321, L71
Casali, M. M. 1995, private communication
Casali, M. M., Eiroa, C., & Duncan, W. D. 1993, A&A, 275, 195
Cohen, M., Dopita, M. A., & Schwartz, R. 1986, ApJ, 302, L55
Cohen, M., Harvey, P. M., Schwartz, R. D., & Wilking, B. A. 1984, ApJ, 278, 671
D'Antona, F., & Mazzitelli, I. 1994, ApJS, 90, 467
de Lara, E., Chavarria-K., C., & López-Molina, G. 1991, A&A, 243, 139
Eiroa, C., & Casali, M. M. 1992, A&A, 262, 468
Eislöffel, J., Günther, E., Hessman, F. V., Mundt, R., Poetzel, R., Carr, J. S., Beckwith, S., & Ray, T. P. 1991, ApJ, 383, L19
Elias, J. H. 1978, ApJ, 224, 857
Elias, J. H., Frogel, J. A., Matthews, K., & Neugebauer, G. 1982, AJ, 87, 1029
Goodrich, R. W. 1987, PASP, 99, 116
Graham, J. A., & Frogel, J. A. 1985, ApJ, 289, 331
Greene, T. 1995, private communication
Hartmann, L., & Kenyon, S. J. 1987, ApJ, 312, 243
Hartmann, L., Kenyon, S., & Hartigan, P. 1991, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: Univ. Arizona Press), 497
Hartmann, L., Kenyon, S. J., Hewett, R., Edwards, S., Strom, K. M., Strom, S. E., & Stauffer, J. R. 1989, ApJ, 338, 1001
Haslam, C. G. T. 1974, A&AS, 15, 333
Herbig, G. H. 1977, ApJ, 217, 693
———. 1989, in ESO Conf. Workshop Proc. 33, Low-Mass Star Formation and Pre-Main-Sequence Objects, ed. B. Reipurth (Garching: ESO), 233
Hodapp, K.-W. 1995, IAU Circ. 6186
Hodapp, K.-W., & Deane, J. 1993, ApJS, 88, 119
Hodapp, K.-W., et al. 1995, Proc. SPIE, 2475, 8
———. 1996, NeWA, submitted
Hodapp, K.-W., Rayner, J., & Irwin, E. 1992, PASP, 104, 441
Hoffmann, W. F., Fazio, G. G., Shivanandan, K., Hora, J. L., & Deutsch, L. K. 1993, Proc. SPIE, 1946, 449
Hurt, R. L., & Barsony, M. 1996, ApJ, 460, L45
Kenyon, S. J., Hartmann, L., & Hewett, R. 1988, ApJ, 325, 231
Kozlowski, L. J., et al. 1994, Proc. SPIE, 2268, 353
Ladd, E. F., Fuller, G. A., Padman, R., Myers, P. C., & Adams, F. C. 1995, ApJ, 439, 771
Liseau, R., Lorenzetti, D., & Molinari, S. 1992, A&A, 253, 119
McMullin, J. P., Mundy, L. G., Wilking, B. A., Hezel, T., & Blake, G. A. 1994, ApJ, 424, 222
Mundt, R., Stocke, J., Strom, S. E., Strom, K. M., & Anderson, E. R. 1985, ApJ, 297, L41
Petrov, P. P., & Herbig, G. H. 1992, ApJ, 392, 209
Reipurth, B., Chini, R., Krügel, E., Kreysa, E., & Sievers, A. 1993, A&A, 273, 221
Sandell, G. 1994, MNRAS, 271, 75
Sargent, A. I., & Beckwith, S. V. W. 1987, 323, 294
Shure, M. A., Toomey, D. W., Rayner, J. T., Onaka, P. M., & Denault, A. J. 1994, Proc. SPIE, 2198, 614
Staude, H. J., & Neckel, Th. 1992, ApJ, 400, 556
Strom, S. E., Vrba, F. J., & Strom, K. M. 1976, AJ, 81, 638
Weintraub, D. A., Sandell, G., & Duncan, W. D. 1989, ApJ, 340, L69