We present post-outburst observations of the mid-infrared spectrum and submillimeter continuum of the illuminating source of the newly discovered McNeil’s Nebula in the L1630 region of Orion. The 12 μm flux of this source has increased by a factor of ~25 after the outburst, whereas the submillimeter continuum remains at its pre-outburst level. The bolometric luminosity has increased by at least an order of magnitude, to ~34 $L_{\odot}$, and is likely less than 90 $L_{\odot}$. The mid-infrared spectrum exhibits a strong and red continuum with no emission or absorption features. The infrared slope of the spectral energy distribution identifies the illuminating source as a flat-spectrum protostar, in both its active and quiescent states. New CO spectral line observations show no evidence of a molecular outflow.

Subject headings: stars: formation — stars: pre–main-sequence — stars: variables: other
In the active state, the outburst SED of MNO, we obtain between 2 and 12 m flux densities measured in two different sized apertures, the circumstellar structure responsible for the submillimeter emission must also be compact, and $\leq 10^4$ AU in diameter, if we assume the accepted distance of $d \sim 450$ pc for L1630.

Contrary to the behavior of the optical and infrared spectrum of MNO, no changes are apparent in the submillimeter continuum ($350 \mu m \leq \lambda \leq 1.3$ mm) as a result of the current activity. Assuming the Rayleigh-Jeans limit and optically thin emission, the submillimeter flux density follows the relationship $F_\nu \propto \nu^{2+n}$, where $\nu$ is the power-law index of the grain opacity. A least-squares fit to the four submillimeter points in the $(\log \nu, \log F_\nu)$-plane gives $\nu = 0.65 \pm 0.19$. The slightly more sophisticated model of Mitchell et al. (2001, their eq. [2]), if applied to the 450 and 850 m measurements, yields a range of $\nu$ between 0.79 and 1.24 (for dust temperature values $T_{dust} \sim 50$ and 20 K, respectively). The discrepancy in $\nu$ between a simple fit and the Mitchell et al. (2001) model may indicate that the material is not optically thin and/or the Rayleigh-Jeans approximation is inappropriate. The value of $\nu$ is apparently near unity, although we caution that it would be best determined with a full SED model fit if more far-infrared data become available while MNO is in an active state.

Figure 2 shows the mid-infrared spectrum of MNO from 7.5 to 12.5 m. The spectrum exhibits a bright, red, featureless continuum across the N band. A simple power-law fit to the continuous spectrum gives $F_\nu \propto \nu^{2+n}$, which corresponds to $n = -1.5 \pm 0.1$. The positions of various solid-state features that are commonly seen in the spectra of other YSOs are labeled in Figure 2, although none of them are detected here. The flux densities at 450 and 850 m measured in our SCUBA observations of MNO are $1.589 \pm 0.099$ and $0.316 \pm 0.005$ Jy beam$^{-1}$ (quoted errors are 1 $\sigma$ statistical uncertainties), respectively, and correspond to FWHM apertures of $\sim 9''$ and $\sim 14''$, respectively. Our 850 m flux density is essentially identical to the value cited by Mitchell et al. (2001) for a $\sim 20''$ diameter aperture, based on SCUBA maps of L1630 made by those authors in 1998. Lis et al. (1999) have argued that the 1.3 mm emission is confined within a deconvolved diameter of less than 3''. Given the agreement between the 850 m flux densities measured in two different sized apertures, the circumstellar structure responsible for the submillimeter emission must also be compact, and $\leq 10^4$ AU in diameter, if we assume the accepted distance of $d \sim 450$ pc for L1630.

Consistent with the factor of $\sim 16$ near-infrared brightening of MNO, the 12 m flux density rose by a factor of $\sim 25$ during the high state. In the standard classification scheme for YSOs (Lada & Wilking 1984; Adams et al. 1987; André et al. 2000), an SED type is assigned from the logarithmic slope of the spectrum, $n$, where $\nu F_\nu \propto \nu^n$. For the conventional infrared indices of the post-outburst SED of MNO, we obtain $n = -0.62 \pm 0.14$ between 2 and 10 m (corresponding to the $K - N$ color) and $n = -0.66 \pm 0.13$ between 2 and 12 m. The 2MASS 2 m and IRAS 12 m points from the quiescent phase of MNO yield an index of $n = -0.35 \pm 0.18$. The foregoing values of the SED slope in the infrared establish MNO as a flat-spectrum/Class I object regardless of its activity level.

Footnote 1: These indices are calculated from flux measurements taken $\sim 5$ weeks apart and are therefore subject to any changes in the near-infrared fluxes during that time.
are offset in by 3 K for clarity. The dotted lines mark velocity offsets of its offset in declination in arcminutes from the position of MNO. The spectra Each spectrum is the average in a 1

4.—Composite CO J = 2–1 spectra from the region surrounding MNO.

Each spectrum is the average in a 1" diameter aperture, labeled according to its offset in declination in arcminutes from the position of MNO. The spectra are offset in T by 3 K for clarity. The dotted lines mark velocity offsets of ±3 km s⁻¹ from the rest velocity of the L1630 cloud.

4. DISCUSSION

As shown above and discussed by Ábrahám et al. (2004), the small (slightly negative) infrared spectral index, n, establishes MNO as a flat-spectrum/Class I object. The large spectral slope in the submillimeter is also more typical of Class I sources than the presumably more evolved Class II sources (Dent et al. 1998). It is worthwhile to compare MNO with the other young outflow sources in L1630 since it is reasonable to assume these other objects, as siblings of MNO, may experience similar outbursts. Using our data and the flux values given by Mitchell et al. (2001), we note that the 850 μm flux decreases by a factor of 4 between the Class 0 (e.g., HH 24 MMS and HH 25 MMS) and Class I (e.g., SSV 59 and SSV 63EW) objects in L1630, and by another factor of 4 from the Class I objects to MNO. With an appropriate correction for distance, flat-spectrum sources in other clouds have 850 μm fluxes similar to that of MNO (e.g., HL Tau). Applying the standard assumption of optically thin, isothermal dust (cm² g⁻¹, T_dust = 50 K; Beckwith 1999), we infer from the 850 μm flux a total (gas + dust) circumstellar mass of Mₙ ~ 0.06 M☉. Our mass estimate is an order of magnitude lower than that calculated by Ábrahám et al. (2004), primarily due to the different T_dust assumed. Nevertheless, Mₙ is significantly larger than the values typically found for Class II disks. The submillimeter evidence therefore agrees well with the interpretation from the infrared SED that MNO is currently in transition from the Class I to Class II stage of protostellar evolution. The circumstellar environment of MNO is probably dominated by a massive accretion disk, with only a remnant envelope structure.

The mid-infrared spectrum of MNO shown in Figure 2 is notably devoid of any solid-state spectral features. None of the three major polycyclic aromatic hydrocarbon (PAH) features (at 7.7, 8.6, and 11.2 μm) are seen, in agreement with the absence of the more frequently detected 3.3 μm PAH feature in the 1–5 μm spectrum presented by Vacca et al. (2004). PAH features are seldom observed in low-mass YSOs (Smith et al. 1989; Brooke et al. 1999) but are more common in their higher mass counterparts, the Herbig Ae/Be stars (Ressler & Barsony 2003; Habart et al. 2004). There is no evidence of 3.3 μm PAH emission in the infrared spectra of the other Class I objects in L1630 discussed by Simon et al. (2004). More puzzling is the absence of a 9.7 μm amorphous silicate feature in the spectrum of MNO. According to Cohen et al. (1984), at least two of the other Class I objects in L1630 (SSV 59 and 63) have strong silicate absorption bands. The optical depth of the 3.1 μm H₂O ice band measured by Vacca et al. (2004), τ_H₂O ~ 0.7, suggests that the 9.7 μm feature of MNO should also be in absorption. Using information provided by Brooke et al. (1999, their Fig. 8), we would expect a band depth of τ(9.7 μm) ~ 0.4. Such a shallow absorption could be entirely filled in by emission from the optically thin surface layers of a disk if it is viewed at a suitably high inclination angle (Chiang & Goldreich 1999, their Fig. 5).

Recent VLA observations at wavelengths of 3.6, 6, and 20 cm detected no radio emission from MNO to rms noise levels of 42, 48, and 140 μJy, respectively (M. Claussen 2004, private communication). The flux densities expected from dust, based on an extrapolation from the submillimeter wavelengths, fall below these detection limits. Of the Class I sources in L1630, radio detections have been reported previously for SSV 63 (three separate components; Reipurth et al. 2002) and HH 26 IR, whereas SSV 59 has a 3 σ upper limit of 66 μJy (Gibb 1999). The radio emission from objects like SSV 59 and MNO is either absent or optically thick.

The lack of an obvious high-velocity jet or molecular outflow from MNO remains to be explained and further distinguishes this object from the other YSOs in L1630. Although a powerful wind is evident in post-outburst optical and infrared spectra, shocked emission from the standard optical and infrared forbidden lines is absent (Reipurth & Aspin 2004; Briceño et al. 2004; Vacca et al. 2004). The submillimeter CO spectral line maps obtained by us and by Lis et al. (1999) show no spatial distinction between redshifted and blueshifted emission. The limited spatial resolution of these maps does not definitively rule out the presence of a molecular outflow, and so interferometric observations will be required to address this issue appropriately. However, as shown in Figure 3, our single-dish observations do rule out the presence of gas moving at velocities greater than ~3 km s⁻¹ from the rest velocity of the L1630 cloud. The best candidate outflow signatures from MNO are the HH 23 clumps of [S ii] emission, which are located ~3° to the north, along the direction of McNeil’s Nebula (Eisloffel & Mundt 1997; Lis et al. 1999; Reipurth & Aspin 2004).

Using a simple trapezoidal integration of the SEDs shown in Figure 1, we estimate that the bolometric luminosity of MNO has changed from ~3.5 to 34 L☉ during the outburst. The post-outburst value of L bol was estimated by Lis et al. (1999) to be 2.7 L☉ and by Ábrahám et al. (2004) to be 5.6 L☉. The former result is identical to ours when allowance is made for the different distances that were used. The Ábrahám et al. (2004) value is slightly larger than ours because those authors chose to correct for an assumed (nonlocal) extinction of A_v = 13 mag. However, such a correction leads to an overestimate of L bol if the extinction is due to local circumstellar material (as is thought to be the case for MNO) because the short-wavelength flux is thermalized and then reemitted at longer wavelengths. Our post-outburst value of L bol likely understimates the true value because we lack information in the SED near its peak in the far-infrared. We have used a linear extrapolation between the infrared and submillimeter portions of the SED to estimate a peak flux of ~80 Jy (at roughly 70 μm), which leads to an upper limit on the post-outburst L bol ≤ 90 L☉.

Briceño et al. (2004) have calculated an intrinsic luminosity
of the post-outburst MNO of $L = 219 L_\odot$ from their $I$-band data, assuming that the spectral type is A0 V and that $A_I = 7.2$, or $A_V \sim 15$. However, the post-outburst colors of MNO suggest a lower extinction of $A_V \sim 11$ (Reipurth & Aspin 2004), which is in agreement with the value indicated by the depth of the infrared H$_2$O ice band (Vaccia et al. 2004). Using the interstellar extinction law of Mathis (1990), the main-sequence colors and bolometric corrections of Kenyon & Hartmann (1995), and the lower post-outburst extinction value, the Briceño et al. (2004) luminosity is reduced by more than a factor of 4, to $L_{bol} \sim 47 L_\odot$ (this assumes $R_V = 3.1$; the value would be roughly a factor of 2 larger if $R_V = 5.0$). The revised value is thus in good agreement with the estimate obtained by integrating under the SED.

Both analyses, all the same, should be treated with some caution. In the post-outburst stage, there will be a considerable contamination of the $I$-band magnitudes from scattering in McNeil’s Nebula (particularly with the large pixel scale in those observations). Moreover, it is not at all clear that main-sequence colors and bolometric corrections apply to YSOs like MNO. At the same time, a simple integration of the SED includes any luminosity from accretion and consequently may not be an accurate representation of the intrinsic photospheric flux (including the portion that is thermalized by local dust and reemitted at longer wavelengths). With those caveats in mind, the $L_{bol}$ values both before and after the outburst do not support earlier claims that MNO is a B-type star, to order of magnitude but still remains low compared to that expected from either an early-type photosphere or a FU Orionis star. Our limited CO spectral line maps indicate that no high-velocity flows of molecular gas have yet appeared in the immediate vicinity of this object. Far-infrared observations of MNO from the Spitzer Space Telescope would help to complete the post-outburst SED and aid in determining $L_{bol}$ and $T_{dust}$, and thus $M_{dot}$, providing important evolutionary constraints on this object. Observations of solid-state features in the mid- and far-infrared spectrum of MNO would also serve to provide a constraint on the disk inclination angle and thus would offer a test of our explanation for the absence of the 9.7 $\mu$m feature.

We are grateful to Tom Kerr, Sandy Leggett, Thomas Lowe, Sandrine Bottinelli, and Jonathan Williams for their assistance with the observations and data reduction. Suggestions from an anonymous referee have greatly improved this Letter. We also want to thank Mark Claussen, Mike Cushing, Joel Kastner, Bo Reipurth, and Bill Vaccia, who have generously shared their results before publication.

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The bolometric luminosity has increased by (at least) an order of magnitude but still remains low compared to that expected from either an early-type photosphere or a FU Orionis star. Our observations in the mid- and far-infrared spectrum of MNO would also serve to provide a constraint on the disk inclination angle and thus would offer a test of our explanation for the absence of the 9.7 $\mu$m feature.

5. SUMMARY

We have presented new observations in the mid-infrared and submillimeter of the outburst star that illuminates McNeil’s Nebula. The object has brightened by a factor of $\sim 25$ in the mid-infrared yet remained at the same brightness in the submillimeter. The bolometric luminosity has increased by (at least) an order of magnitude but still remains low compared to that expected from either an early-type photosphere or a FU Orionis star. Our observations in the mid- and far-infrared spectrum of MNO would also serve to provide a constraint on the disk inclination angle and thus would offer a test of our explanation for the absence of the 9.7 $\mu$m feature.

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