A YOUNG VERY LOW MASS OBJECT SURROUNDED BY WARM DUST

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ABSTRACT

We present a complete low-resolution (R ~ 100) near-IR spectrum of the substellar object GY11, a member of the ρ Ophiuchi young association. The object is remarkable because of its low estimated mass and age and because it is associated with a mid-IR source, an indication of a surrounding dusty disk. Based on the comparison of our spectrum with similar spectra of field M dwarfs and atmospheric models, we obtain revised estimates of the spectral type, effective temperature, and luminosity of the central object. These parameters are used to place the object on a H-R diagram and to compare it with the predictions of pre–main-sequence evolutionary models. Our analysis suggests that the central object has a very low mass, probably below the deuterium-burning limit and in the range of 8–12 M_j, and a young age of less than 1 Myr. The IR excess is shown to be consistent with the emission of a flared, irradiated disk similar to those found in more massive brown dwarf and T Tauri systems. This result suggests that substellar objects, even the so-called isolated planetary mass objects, found in young stellar associations are produced in a similar fashion as stars, by core contraction and gravitational collapse.

Subject headings: infrared: stars — stars: atmospheres — stars: fundamental parameters — stars: low-mass, brown dwarfs

On-line material: color figures

1 INTRODUCTION

The discovery of brown dwarfs (BDs) and objects with masses comparable to those of giant planets (well below the deuterium-burning limit M < 13 M_j) “free floating” in young stellar clusters (Zapatero-Osorio et al. 2000; Lucas & Roche 2000) has opened an interesting debate on their origin. Do they form like ordinary stars from the collapse of molecular cores (Shu, Adams, & Lizano 1987)? If so, the very existence of very low mass objects and their mass function put strong constraints on star formation theories. Alternatively, BDs and isolated planetary mass objects may be stellar “embryos” ejected from multiple forming systems before reaching a stellar mass (Reipurth & Clarke 2001), or they may form like planets by coagulation of dust particles and subsequent gas accretion within circumstellar protoplanetary disks (Lin et al. 1998). Young (proto)planets could then be extracted or ejected by dynamical interactions from the forming planetary systems. In this scenario, isolated BDs and planetary mass objects are intrinsically different from stars; their study sheds no light on star formation theories but provides instead a chance of studying the early evolution of giant planets where they can be observed in isolation, rather than very close to a much brighter star.

One way to shed light on the origins of very low mass objects is to ascertain their association with circumstellar disks, which are characteristic of stellar formation from the contraction of a molecular core. Deep images in the L band (Muench et al. 2001) and in the mid-IR (Persi et al. 2000; Bontemps et al. 2001) have shown that many very low luminosity objects have excess emission at these wavelengths, and detailed studies of some of them have proved that the central objects are bona fide BDs. Their IR excess is consistent with the presence of a surrounding disk similar to those found around more massive pre–main-sequence stars (Comerón et al. 1998; Comerón, Neuhäuser, & Kaas 2000; Natta & Testi 2001). These initial findings, albeit limited, seem to suggest that indeed BDs form like ordinary stars.

We report here the first results of a project aimed on one hand to improve our understanding of disks around BDs, following the approach of in Natta & Testi (2001), and on the other hand to find evidence of a circumstellar disk around bona fide isolated planetary mass objects.

We have used the Near-Infrared Camera and Spectrograph (NICS) on the 3.56 m Telescopio Nazionale Galileo to acquire low-resolution (near-IR) spectra of a sample of mid-IR sources located within the ρ Ophiuchi cloud (Bontemps et al. 2001). Our target list included objects detected at 6.7 and 14.3 μm with the ISOCAM on board the Infrared Space Observatory (ISO; Kessler et al. 1996; Cesarsky et al. 1996), having low effective temperature ($T_{\text{eff}}$), luminosity ($L_\star$), and extinction ($A_\lambda$) based on photometric or limited 2.2 μm spectroscopic estimates. The goal of our new observations was to obtain improved determinations of these parameters and to derive accurate values of masses and ages of the targets by comparison with theoretical evolutionary tracks. The results for the complete sample will be discussed in a future paper (Natta et al. 2002). In this Letter we report on one of the sources, source 33 of the ISOCAM list of Bontemps et al. (2001), which is associated with the near-IR source GY11 (Greene & Young 1992). The substellar nature of this object was already proposed by Rieke & Rieke (1990) and confirmed by Comerón et al. (1998) and Wilking, Greene, & Meyer (1999). We derive a new accurate spectral classification of GY11 and of its effective temperature and luminosity. Our data suggest that GY11 is a planetary mass object, with an IR excess that can be roughly
OBSERVATIONS

A near-IR low-resolution spectrum of GY11 was obtained with the Telescopio Nazionale Galileo (TNG) on La Palma on 2001 July 9, using a 0.5′ slit and the high-throughput low-resolution prism-based disperser unique to NICS (Baffa et al. 2001), the Amici device (Oliva 2000); this setup offers a complete near-IR spectrum, 0.85–2.35 μm, at R ~ 100 across the entire range, and it allows an accurate classification of faint and cool dwarfs (Testi et al. 2001). Instrumental and telluric correction was ensured by observations of A0 stars. The shape of the final spectrum was checked using near-IR photometric measurements from the Two Micron All Sky Survey (2MASS) second incremental data release; synthetic magnitudes were computed using the appropriate transmission curves and compared with the source photometry, and colors were found to be consistent with those of 2MASS to within 10%, as expected from typical uncertainties. To better constrain the values of the extinction, we also obtained optical i-band (0.77 μm) photometry at the ESO La Silla 1.54 m Danish Telescope using the Danish Faint Object Spectrograph and Camera. Photometric calibration was ensured by observations of a set of Landolt (1992) standard stars, converted into the Gunn system using the transformations given by Fukugita et al. (1996).

CENTRAL SOURCE PARAMETERS

Bontemps et al. (2001) associated the ISOCAM source 33 with a class II object member of the ρ Oph young stellar cluster known as GY11 (Greene & Young 1992). The BD nature of GY11 has been suspected for some time (Rieke & Rieke 1990). However, there is a large uncertainty in the literature as to the exact value of its photospheric parameters and mass. Bontemps et al. (2001) estimated bolometric luminosity and extinction to be L∗ ~ 0.001 L⊙, Aµ ~ 2.7 mag from near-IR photometry. Based on multiband IR photometry and a 2.2 μm low-resolution spectrum, Wilking et al. (1999) estimated a spectral type M6.5, Aµ ~ 5 mag, L∗ ~ 0.002 L⊙, and Teff ~ 2650 K. These authors noted that owing to veiling caused by dust emission, the spectral type could easily be some 2–3 subclasses later, and the extinction would be significantly underestimated. In fact, Comerón et al. (1998) derive a higher value of Aµ = 10 mag from broadband photometric measurements that include optical and IR bands.

Our complete near-IR spectrum offers the possibility of a better estimate of the source parameters, as it allows us to use the global spectrum shape below 2 μm, a region that is less affected by the continuum veiling due to the dust emission. Given the expectation that the surface gravity of very young BDs should be similar to that of subgiants, we derive the photospheric parameters by comparison with field dwarf spectra and model atmospheres with appropriate surface gravity, as suggested by the evolutionary models (Comerón et al. 2000). We first derive extinction and spectral type by matching the observed GY11 spectrum with that of field dwarfs in the solar neighborhood (L. Testi et al. 2002, in preparation), obtained with the same instrumental setup and reddened using the Cardelli, Clayton, & Mathis (1989) extinction law most appropriate for Ophiuclus (Rv = 4.2; Fig. 1a). We try to provide the best fit to the global shape of the spectrum, with particular attention to the H-band shape, the J-band features, and the drop due to water vapor absorption at the red edge of the J band.

Overall, the best spectral match is found with the field dwarf with spectral type M8.5 and extinction Aµ ~ 7.0 mag. Lower values of Aµ (by ~1 mag) offer a better match of the spectrum with later dwarf spectra (M9–L0) but are not consistent with the broadband optical measurements (see Fig. 4, inset). A higher value of the extinction causes a too steep rise of the spectrum below 1.2 μm. Field dwarfs with spectral types earlier than M7.5 show large deviations from the observed shape of the H band and the drop at 1.3 μm. Given the uncertainties of a classification based on objects with very different surface gravity, we expect our classification to be accurate within one spectral subclass and the visual extinction estimate to be accurate within 1 mag.

As a second step, in order to derive an estimate of the photospheric effective temperature (Fig. 1a), we compare the observed GY11 spectrum with reddened, appropriate surface
Fig. 2.—H-R diagram for three sets of evolutionary tracks (D’Antona & Mazzitelli 1997; Chabrier et al. 2000; Burrows et al. 1997). Position of GY11 is shown as a blue circle. Tracks are labeled with the appropriate mass, hydrogen-burning stars are shown in red, deuterium-burning BDs in green, and objects below the deuterium-burning limit in cyan. Isochrones are shown as dotted lines and are labeled with the appropriate ages. [See the electronic edition of the Journal for a color version of this figure.]

Gravity (log g = 3.5) model atmospheres (Allard, Hauschildt, & Schweitzer 2000; Chabrier et al. 2000). The best estimate of the effective temperature is ~2400 ± 100 K. Higher temperature models offer a better match of the H-band shape but underestimate the drop near 1.3 µm and the global shape of the spectrum at the J band. The derivation of the effective temperature of young dwarfs based on theoretical synthesis of the near-IR spectrum is very uncertain (Lodieu et al. 2002); however, our value of $T_{\text{eff}}$ for an object of spectral type M8.5 is consistent with the spectral type versus effective temperature scale discussed by Wilking et al. (1999) and marginally higher than the latest effective temperature scales derived for field dwarfs (Leggett et al. 2001).

To estimate the luminosity ($L_*$) of the object, we used the 2MASS J-band magnitude, dereddened by $A_V \sim 7.0$ mag, and the bolometric correction derived from the best-fitting (2400 K) atmospheric model. The value of this “theoretical” bolometric correction is nearly identical to the empirical value adopted by Wilking et al. (1999). We derive a value of $L_* \sim 0.008 L_\odot \pm 30\%$.

Using the $L_*$ and $T_{\text{eff}}$ values derived above, we can compare the position of GY11 in the H-R diagram with the predictions of theoretical pre–main-sequence evolutionary models. In Figure 2 we show this comparison for the latest release of evolutionary tracks from three leading groups in the theory of pre–main-sequence evolution of substellar objects. In spite of the relatively large uncertainties on $L_*$ and $T_{\text{eff}}$ and the limited accuracy of pre–main-sequence evolutionary tracks at these ages and masses, we confirm that GY11 is a young ($\tau < 1$ Myr), very low mass object, probably below or very close to the deuterium-burning limit, with a best mass estimate in the range 8–12 $M_J$.

### 4. Infrared Excess and Disk Models

GY11 is the lowest mass object with a clearly detected IR excess. It is detected by ISOCAM in the two broadband filters LW2 and LW3 (λ$_{\text{eff}}$ = 6.7 and 14.3 µm, respectively) used by Bontemps et al. (2001) in their ρ Oph survey, as well as in the three intermediate-band filters, SW1, LW1, LW4 (λ$_{\text{eff}}$ = 3.6, 4.5, and 6.0 µm, respectively), used by Comerón et al. (1998) in their pointed observations of optically identified candidate BDs. The ISOCAM measurements in the broad and narrow bands are in good agreement within the flux calibration uncertainties, which we assume to be ~20%.

As usual with ISOCAM, the ~6” beam includes multiple sources seen in higher resolution near-IR images, which may contribute to the observed fluxes. Figure 3 compares a $K_s$ image of the region around GY11 extracted from the Very Large Telescope (VLT) ESO archive (originally observed as part of ESO proposal 63.I-0691) and the ISOCAM LW1 (λ$_{\text{eff}}$ = 4.5 µm) image from the ISO archive (Comerón et al. 1998). The mid-IR emission peaks very close to the position of GY11. Although a small contamination from the near-IR source ~8” to the east is
possible, we think that most of the mid-IR observed flux comes from GY11; a similar conclusion was also reached by Comerón et al. (1998).

In Figure 4 we show the spectral energy distribution (SED) of GY11 at all wavelengths and compare it to that of an irradiated, flared disk similar to those that reproduce the observed characteristics of T Tauri systems (Chiang & Goldreich 1997). The disk has a dust mass of 1 (≈3% of the mass of the central object, for an assumed gas-to-dust mass ratio of 100) and is heated by a central source with the GY11 temperature, luminosity, and mass. We show the predicted SED when the disk extends inward to the stellar surface (solid line) and when it has an inner hole of 3 (dotted line). More details on the disk models can be found in Natta & Testi (2001) and Natta et al. (2002). The agreement between observed and predicted fluxes is rather good, especially for the disk with the large inner hole. In particular, both models predict total (star + disk) fluxes that in the J, H, and K bands are smaller than the calibrated TNG fluxes by 15% at most.

As an independent check, we computed optical and near-IR broadband magnitudes from the model-predicted SED. They are compared in the inset of Figure 4 with the observed dereddened magnitudes in i (this Letter), R, I, L′ (Comerón et al. 1998), J, H, and K (2MASS) bands. The agreement is again quite good.

The ISOCAM measurements, especially that at 14.3 μm, have large error bars, and one should not overinterpret them. However, it is of some interest to point out that if indeed the mid-IR excess is due to disk emission, the disk must be flared. Therefore, dust and gas must be well mixed, as in the majority of pre–main-sequence stars, and no major settling of the dust onto the disk midplane has occurred during the lifetime of GY11. The disk must be optically thick to mid-IR radiation; this, however, sets only a lower limit to the disk mass of roughly 10^{-5} to 10^{-4} M_☉, depending on the exact value of the dust mid-IR opacity and surface density profile. Note that the disk mass has to be very small; if we assume the ratio of the disk mass to the mass of the central object typical of T Tauri stars (0.03), then the disk mass is about 3 × 10^{-4} M_☉, and the disk contains only 1 M_☉ of dust. As a consequence, the accretion rate (if any) is also likely to be low, with an average value over the lifetime of the object that cannot exceed 3 × 10^{-10} M_☉ yr^{-1} (for an age of 1 Myr). The accretion luminosity is also small, about 40 times lower than the luminosity of the photosphere. A direct determination of the disk mass can be derived from (sub)millimeter wavelength observations. We predict for GY11 a 1.3 mm flux of about 0.6 mJy, which is well below the upper limit set by the survey of Motte, André, & Neri (1998), but within the expected capabilities of the Atacama Large Millimeter Array.

5. CONCLUSIONS

The results presented in this Letter show evidence that a young isolated planetary mass object in ρ Oph, with a mass of about 10 M_☉, is surrounded by warm dust, possibly distributed on a disk similar in properties to those around young BDs and T Tauri stars. The implications of this finding, that should be confirmed by higher spatial resolution mid-IR observations and should be extended to a large sample of similar objects, are profound, since they give a clear indication that isolated BDs and even planetary mass objects form like stars and are not produced in a planet-like fashion within protoplanetary disks around more massive objects and later ejected by dynamical interactions. Isolated BDs and planetary mass objects are thus an extension of the stellar and substellar sequence to very low masses and have different origins from “planets.”

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