

NGC 1333 IRAS 4: A VERY YOUNG, LOW-LUMINOSITY BINARY SYSTEM

GÖRAN SANDELL, COLIN ASPIN, AND WILLIAM D. DUNCAN

Joint Astronomy Centre, 665 Komohana Street, Hilo, HI 96720

ADRIAN P. G. RUSSELL

Max-Planck-Institut für Extraterrestrische Physik, Garching bei München, D-8046, Germany

AND

E. IAN ROBSON

Lancashire Polytechnic, School of Physics and Astronomy, Preston PR1 2TQ, Lancashire, U.K.

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ABSTRACT

We present submillimeter photometry and high spatial resolution 800 μm and 450 μm maps of the cold, low-luminosity source IRAS 4 ($T_d = 33$ K, $L \sim 28 L_\odot$) in the active star formation region NGC 1333. IRAS 4 is resolved into a binary system, with components separated by $\sim 31''$ and connected by a bridge of faint dust emission. The submillimeter flux density from the two components is unusually bright [$S_{4A}(800 \mu\text{m}) \sim 12.7$ Jy; $S_{4B}(800 \mu\text{m}) \sim 8.6$ Jy]; IRAS 4A is marginally resolved into a disklike structure 3200×2200 AU in size. The spectral energy distribution of 4A is best explained by optically thick dust emission shortward of 1.1 mm. We derive a total gas and dust mass of $9.2 M_\odot$ for 4A and $4.0 M_\odot$ for 4B. These correspond to average gas densities of $9.0 \times 10^9 \text{ cm}^{-3}$ and $9.2 \times 10^8 \text{ cm}^{-3}$, respectively, and imply a line-of-sight visual extinction of $\sim 7 \times 10^4$ mag and $\sim 1 \times 10^4$ mag for 4A and 4B, respectively. The dust masses associated with the binary components are by far the largest seen toward any star of comparable luminosity and are a factor of 10 higher than predicted by theoretical models of protostars. We propose that we are seeing an extremely young stellar system, possibly a true protostar, in which most of the luminosity is the result of the accretion process.

Subject headings: infrared: sources — interstellar: grains — stars: accretion — stars: formation — stars: pre-main-sequence

1. INTRODUCTION

IRAS 4 in NGC 1333 ($d \sim 350$ pc) was first identified as a site of active star formation with the detection of the extremely variable H_2O masers C and D (Haschick et al. 1980; Sandell & Olofsson 1981; Moran 1983). Pointed *IRAS* observations by Jennings et al. (1987, hereafter JCCH87) revealed a cold, low-luminosity source ($T_d = 33$ K; $L = 21 L_\odot$) in the direction of the two masers. Liseau, Sandell, & Knee (1988, hereafter LSK88) reported a faint CO outflow in the vicinity of IRAS 4 but did not study it in detail. None of the above make IRAS 4 unique, and although it is the coldest object in the sample of JCCH87 it was taken to be yet another young low-mass star.

In this *Letter*, we present results of submillimeter photometry and 800 μm and 450 μm mapping of the IRAS 4 region. We find that IRAS 4 is an unusually bright double source at submillimeter wavelengths (both components being associated with H_2O masers), and presumably much younger than previously believed. In fact, IRAS 4 appears to be one of the most promising candidates for a young protostellar system, still in its accretion phase.

2. OBSERVATIONS

The observations reported in this *Letter* were made with the common user bolometer UKT14 (Duncan et al. 1990) on the James Clerk Maxwell Telescope¹ on Mauna Kea, Hawaii,

during three nights in 1990 August. Some additional photometry was obtained in 1990 November, and the diffraction-limited 450 μm maps were obtained during 1991 January 11 and January 13.

The observing conditions were reasonably good during all observing runs. The sky transmission was monitored by frequent observations of Mars and by doing sky dips with the UKT14 calibration unit (Duncan et al. 1991). Variations in sky opacity were also followed using the 1.3 mm optical depths from the sky monitor at the adjacent Caltech Submillimeter Observatory. Pointing was checked frequently by offsetting from 3C 84 and was never in error by more than a few arcseconds. All photometry was performed with a $60''$ east-west chop using a fully open aperture, which gives a nearly constant beam width as a function of frequency (Duncan et al. 1990). The results of the submillimeter photometry are given in Table 1, and the spectral energy distribution (SED) of IRAS 4A and B is shown in Figure 1 together with the *IRAS* data points from JCCH87.

The 800 μm mapping was performed in horizontal coordinates in “on-the-fly” mode with a diffraction-limited beam (HPBW $\sim 13.5''$) using an east-west chop of $40''$, a sampling interval of $5''$, and an integration time of 2 s pixel^{-1} . The total area mapped was $125'' \times 125''$. Two maps were taken and independently calibrated, restored, and transformed to equatorial coordinates using the standard continuum package NOD2 (Haslam 1974). The final map is presented in Figure 2 (*left*). The total integrated flux in the map is ~ 27.7 Jy. The calibrated 800 μm map agrees within errors with the photometry in Table 1.

The two 450 μm maps were observed in a similar mode to the 800 μm maps, using a chop throw of $20''$, a sample interval

¹ The James Clerk Maxwell Telescope is operated on a joint basis between the United Kingdom Science and Engineering Research Council (SERC), the Netherlands Organisation for the Advancement of Pure Research (ZWO), the Canadian National Research Council (NRC), and the University of Hawaii (UH).

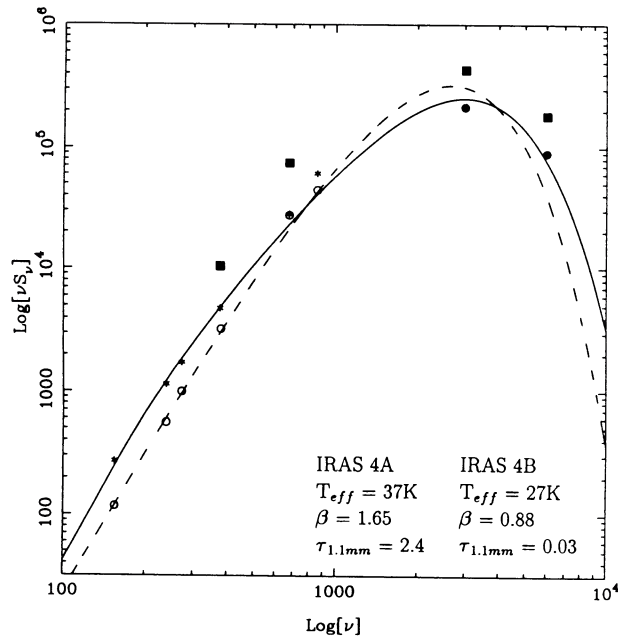


FIG. 1.—The spectral energy distribution of IRAS 4A and 4B derived from the photometry in Table 1 including the *IRAS* 50 μ m and 100 μ m flux densities from JCCH87. We have divided the total *IRAS* flux equally between 4A and 4B. The IRAS 4A points are marked as asterisks, the IRAS 4B points as open circles. The lines represent the best least-squares fit of the dust emission. The derived parameters are given in the lower right-hand corner. The four filled squares at 50, 100, 450, and 800 μ m are the total *IRAS* fluxes and the total integrated fluxes in the 450 μ m and 800 μ m maps.

of 2", and an integration time of 1 s pixel⁻¹. The total area mapped was 90" × 90". Emission can be seen to continue outside the map boundaries. The 450 μ m maps were calibrated from two beam maps of Mars ($D \sim 12''.2$), assuming a HPBW = 7''.7 and an error lobe contribution of 45% in a 60" × 60" area. Some refraction noise, which can broaden the beam (as can slight focus errors or temperature gradients on the backing structure of the dish), was present during the night of January 13. We have independently reduced the two 450 μ m maps. Initially we used a HPBW of 7''.7 for both maps. In this case both 4A and 4B appeared definitely broader in the second map, while the peak flux was lower. We consider that refraction noise had broadened the January 13 map, and so we have recalibrated it using a 8''.5 beam. With this assumption the peak fluxes of the two maps agree to within 6% when smoothed to same resolution. The integrated flux of the two maps is of course more accurate, since they are both calibrated directly from beam maps of Mars. We estimate that the calibration accuracy is $\sim 15\%$ for the integrated flux and $\sim 30\%$ in Jy beam⁻¹, because of the uncertainty in the true HPBW. The integrated flux in the 90" × 90" area is ~ 109 Jy. The final map is presented in Figure 2 (*right*). The total bolometric luminosity of IRAS 4 from our maps is $\sim 28 L_{\odot}$, divided roughly equally between 4A and 4B.

3. MORPHOLOGY AND PHYSICAL CHARACTERISTICS OF IRAS 4

The submillimeter maps (Fig. 2) resolve IRAS 4 into a double source, connected by a bridge a faint emission. This suggests that IRAS 4 is a binary system, where the faint emission originates from a remnant of the progenitor molecular

TABLE 1
NGC 1333 IRAS 4: POSITIONS, SIZES, AND FLUXES

A. POSITIONS				
IRAS 4A	03 ^h 26 ^m 43 ^s .78 ± 0 ^s .09, +31°03'13".6 ± 1".0			
H ₂ O(C) ^a	03 ^h 26 ^m 50 ^s .0, +31°03'40".0 ± 15"			
IRAS 4B	03 ^h 26 ^m 6 ^s .48 ± 0 ^s .09, +31°02'50".8 ± 1".0			
H ₂ O(D) ^b	03 ^h 26 ^m 6 ^s .483, +31°02'50".07 ± 0".12			
B. SIZES				
Map	IRAS 4A	IRAS 4B		
800 μ m	8".2 × 4".8	15".0 × 8".9		
450 μ m	9.1 × 6.2	14.0 × 7.0		
C. FLUXES				
Filter	S_{4A} (Jy beam ⁻¹)	S_{tot} (Jy) ^c	S_{4B} (Jy beam ⁻¹)	S_{tot} (Jy) ^c
2.0 mm	1.63 ± 0.07	1.75	0.64 ± 0.05	0.76
1.3 mm	4.19 ± 0.03	4.76	1.72 ± 0.04	2.32
1.1 mm	5.45 ± 0.02	6.27	2.63 ± 0.02	3.64
800 μ m	10.9 ± 0.3	12.9	5.76 ± 0.15	8.55
450 μ m	35.6 ± 4.2	41.6	28.0 ± 5.0	40.6
350 μ m	61.3 ± 7.0	71.0	36.8 ± 7.0	51.7

^a Position from Haschick et al. 1980.

^b VLA position from Moran 1983 as given by A. D. Haschick, private communication.

^c The total fluxes are likely to be high because the photometry includes contributions from the surrounding extended emission.

Note: Positions of 4A and 4B determined directly from mapping data source sizes derived from Gaussian fits assuming position angle $\sim 138^\circ$ for major axis. For 4A, the 800 μ m fluxes are an average of three observations and the 450 μ m fluxes an average of four observations. For 4B the 800 μ m and 450 μ m fluxes are averages of two observations taken on different days. All other fluxes are from single observations. Quoted errors are statistical errors only and do not include any systematic calibration uncertainties.

cloud. It may still be, however, a dynamically active part of the system, i.e., a circumbinary disk.

Sandell, Aspin, & Robson (1991) find that bipolar outflows tend to show extended dust emission in the outflow direction. For IRAS 4, the molecular outflow lies NE-SW, and the protrusions in this direction seen in Figure 2 may also be the result of dust associated with the outflow.

In the analysis that follows, we only consider component 4A, since it is the brighter source and less affected by the surrounding faint emission. The compact emission associated with 4A is resolved into an elongated structure, and from Gaussian fits to the 450 μ m map (see Table 1) we derive a diameter, D , and a width, h , equal to $D \times h \sim 9''.1 \pm 0''.4 \times 6''.2 \pm 0''.4$, or 3200 × 2200 AU. These values are $\sim 3 \sigma$ from circularly symmetry, and we interpret the emission as a dust disk surrounding the object. However, the analysis and the values of the physical parameters we derive are independent of the assumed source geometry. Using a disk model and assuming that the apparent thickness of the disk is the result of projection effects, the above dimensions would predict an inclination $i \sim 40^\circ$, where $i = 0^\circ$ is edge-on.

Having established a size for the dust emitting region associated with 4A, we can take the observed fluxes (Table 1) and derive a mass. We adopt the dust emissivity by Hildebrand (1983), but chose a β -index of 1.5 rather than 2, because recent observations have shown that the β -index is < 2 longward of 250 μ m (see, e.g., Weintraub, Sandell, & Duncan 1989, 1991; Sandell 1989; Beckwith et al. 1990; Woody et al. 1989). The

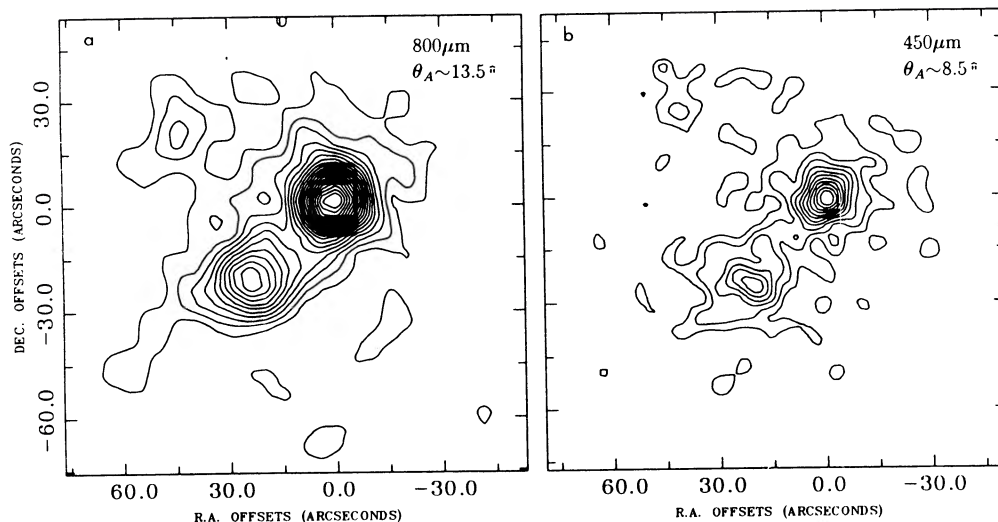


FIG. 2.—Contour maps of the submillimeter continuum emission of IRAS 4 obtained with UKT14 on the JCMT. Axes offsets are in arcseconds from the position of IRAS 4A. The filter and HPBW (θ_A) is given in the upper right-hand corner of each figure. *Left*: the 800 μm map. The lowest contour level is 0.4 Jy beam $^{-1}$ (2σ) with steps of 0.4 Jy beam $^{-1}$ and has a peak flux of 9.8 Jy beam $^{-1}$ for 4A and 5.8 Jy beam $^{-1}$ for 4B. *Right*: The 450 μm map. The lowest contour level is 1.2 Jy beam $^{-1}$ (2σ) with steps of 1.2 Jy beam $^{-1}$ and has a peak flux of 21.8 Jy beam $^{-1}$ for 4A and 12.4 Jy beam $^{-1}$ for 4B.

choice of dust emissivity and β -index represents the largest uncertainties in our mass determination, but as demonstrated below, any reasonable choice of β -index will still result in an unusually large mass. It is also difficult to obtain an accurate determination of the dust temperature in IRAS 4 since it is not resolved by *IRAS*; we therefore take the global value, $T_d = 33$ K, as derived by JCCH87. The uncertainty in this temperature is unlikely to be larger than 50%, and therefore our determination of the dust mass is not likely to be in error by more than 30%.

IRAS 4A (Fig. 1), has a spectral index, $\alpha \sim 2.1$ from 1.1 mm to 350 μm and ~ 2.4 from 1.1 to 2 mm. Component 4B has a spectral index $\alpha \sim 2.7$ from 2 mm to 450 μm . A simple interpretation of the 4A SED is that the dust is optically thick to ~ 1.1 mm. In this case the flux at 2 mm will give the most reliable mass estimate. By assuming that the dust distribution is homogeneous and isothermal, we derive total masses, $M_d(4A) \sim 9.2 M_\odot$ and $M_d(4B) \sim 4.0 M_\odot$. Both estimates are extremely high for a low-luminosity star. Using a conventional β -index of 2 would result in even higher masses. As shown by Emerson (1988), the β -index has to be ≥ 1 , and we stress that even with a $\beta = 1$, $M_d(4A)$ would still be more than $3 M_\odot$.

In addition to the relatively simple derivation above, we have also fitted the SED of IRAS 4A with the disk model developed for FU Ori stars by Weintraub et al. (1991). In this model the free parameters are the β -index and the surface density and temperature at the inner edge of the disk. The 50 and 100 μm *IRAS* photometry is needed to constrain the value of the inner radius and temperature gradient of the disk. We assume here that half the *IRAS* flux is emitted by 4A but note that this may not be very accurate. However, the mass determination is not sensitive to the value assumed, it merely affects the temperature gradient of the disk which is, in this case, already close to being isothermal.

D. A. Weintraub (private communication) finds that the SED of 4A can be fitted with a temperature gradient, $q = 0.38$ ($T \propto r^{-q}$), and $\beta = 0.7$, giving a total mass of the IRAS 4A disk of $\sim 10 M_\odot$. By varying the *IRAS* fluxes, Weintraub finds

good model fits ranging in disk mass from 7 to 55 $M_\odot$; the minimum mass assumes a density gradient, $p = -1.75$ ($n \propto r^p$) while the maximum mass assumes $p = -1.0$. These models predict the dust to be optically thick shortward of 300 μm . Therefore, even when applying a more rigorous treatment to the data, it is difficult to obtain a mass less than 7 $M_\odot$.

If we neglect the inclination of the disks and take the derived sizes as disk diameters and thickness, the masses estimated above correspond to average gas densities $n(4A) > 9.0 \times 10^9 \text{ cm}^{-3}$, and $n(4B) > 9.2 \times 10^8 \text{ cm}^{-3}$. We can also compute a line-of-sight extinction (see, e.g., Sandell 1989); however, we now need to account for the inclination. Assuming that the underlying star is obscured by at most half the disk radius (although it could be considerably less if the disk is thin), we obtain a visual extinction, $A_v(4A) \sim 7 \times 10^4 \text{ mag}$ and $A_v(4B) \sim 10^4 \text{ mag}$. The extinction of 4B will be overestimated if the size of this disk is overestimated. If we assume a spherical dust distribution, with the radius being the geometric mean of the disk size, the extinction is still $\sim 10^4$ for both sources.

The mass of the extended circumbinary material can be estimated from the 800 and 450 μm maps. After removing the compact emission associated with 4A and 4B we find flux densities of ~ 5.7 Jy at 800 μm and ~ 22 Jy at 450 μm . With the same assumptions as above, this corresponds to a total mass of $\sim 1.4 \pm 0.5 M_\odot$. A third emission feature, $\sim 45''$ from the circumbinary disk plane, has an 800 μm flux density of ~ 2.2 Jy and a 450 μm flux density of 9 Jy, corresponding to a mass of $\sim 0.6 \pm 0.2 M_\odot$. This could be material swept up by the outflow from IRAS 4, although we cannot exclude the possibility that it is, or will, evolve into a self luminous star.

4. WHAT IS THE NATURE OF IRAS 4?

Current star formation theories predict that a young (proto)star will be surrounded by a thick envelope or disk of gas and dust still accreting onto the star (see, e.g., Shu, Adams, & Lizano 1987). It is therefore not surprising that most, if not all, young stars appear to be associated with dust emission (Sandell 1989). A priori one would therefore expect the young

gest stars to be most heavily obscured, and to have the coldest and most massive disks. This is indeed predicted by current theoretical models (see, e.g., Adams 1990) and clearly seen in observational data (Sandell 1989; Sandell et al. 1991; Walker, Adams, & Lada 1990; Ladd et al. 1991). Adams (1990) has made an attempt to calculate evolutionary tracks on a luminosity- A_v diagram to characterize the protostellar phase of stellar evolution. Neither 4A nor 4B fit into this scheme. Relative to the total luminosities these extinctions are much too high by more than a factor of 10. Since it is unlikely that our observational data (or the interpretation of them) can be that much in error, it seems that protostellar models still need to be refined if they are to explain the characteristics of extremely young objects like IRAS 4A.

The object most closely resembling IRAS 4 is IRAS 16293–2422 (Walker et al. 1989). This is also a binary system with similar luminosity, but on the whole it appears more evolved. The total luminosity of IRAS 4 is small, yet the mass of the system is outstandingly high. No free-free emission is seen toward IRAS 4 (Rodríguez et al. 1990), nor does it have any near-IR counterparts (Aspin, Sandell, & Russell 1991). There is, however, a CO outflow associated with the IRAS 4 complex (LSK89; see also Knee 1991), and both components are associated with H₂O masers, suggesting that each component is a young star. This may not necessarily be the case,

because accretion can drive mass outflow (see, e.g., Shu et al. 1991), and heat the gas sufficiently to pump the H₂O masers. IRAS 4A appears elongated in our diffraction-limited 450 μ m maps. If we interpret the elongation as a disk, then the disk is large (3000–5000 AU) compared to disk structures hitherto seen toward bipolar outflows and young T Tauri stars (which are typically less than 100 AU). They are, however, comparable to those found in the models by Lin & Pringle (1990), which show that accretion disks, formed during the collapse of a rotating cloud, can be a few thousand AU in size, relatively massive, and long-lived. The Lin & Pringle models also show that the ratio of the disk mass to the stellar mass can be of the order of 10 at the end of the free fall phase. This could well be the case for IRAS 4A, which has an exceptionally large disk mass, yet a modest luminosity. In this case, most of the luminosity could originate from the accretion process rather than from deuterium or hydrogen burning.

In conclusion, we note that our observations and analysis indicate that IRAS 4 is an extremely young object some 10^4 – 5×10^5 yr old and possibly the youngest stellar object yet found.

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