Further observations of IRAS 04302+2247

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ABSTRACT
We present near-infrared broad-band and H$_2$ images of the quadrupolar source IRAS 04302+2247. High-resolution data at 3.8 μm show that the circumstellar envelope has a high degree of axisymmetry: the asymmetry at shorter wavelengths is almost certainly the result of extinction by dust in the cavity. Photometry of the flux peaks confirms that the source is variable but little change in appearance is observed between 1995 November and 1997 September. We report the first clear detection of the molecular outflow in H$_2$ at 2.1 μm, revealing discrete streams which are inclined to the axis of the cavity. The motion of knots in the outflow remains the most likely cause of the variability.

Key words: techniques: photometric – stars: formation – stars: pre-main-sequence – dust, extinction – ISM: individual: IRAS 04302+2247 – infrared: general.

1 INTRODUCTION
Near-infrared imaging of class I protostars allows us to examine the final stages of cloud core contraction with high spatial resolution. Monte Carlo simulations of the scattering and absorption of light by the circumstellar envelope which were developed in the early 1990s (Whitney & Hartmann 1992, 1993; Fischer, Henning & Yorke 1994, 1996) considered axisymmetric structures. However, many class I sources (defined by d(λF$_J$)/dλ > 0 from 2 to 25 μm) display irregular, non-axisymmetric circumstellar envelopes (e.g. Lucas & Roche 1997, hereafter LR1). Non-axisymmetric systems are difficult to analyse because a three-dimensional model has to be constructed from two-dimensional images and simulation with Monte Carlo methods is computer-intensive.

In LR1 we reported the discovery of a highly symmetric quadrupolar structure in the class I source IRAS 04302+2247, which lies in the L1536 cloud in the Taurus–Auriga star-forming region at a distance of 140 pc. The flux distribution and polarization pattern were reproduced by a model in which the system is observed in the equatorial plane (i = 90° ± 4°), which appears as a dark lane oriented approximately north–south. The bright nebulosity on either side of the lane is produced by scattering from the walls of a bipolar cavity in the circumstellar envelope. The unusual feature of the model is the introduction of an optically thick dusty outflow, oriented east–west, which obscures light scattered from the far side of the cavity and causes a dip in surface brightness along the outflow axis, hence the quadrupolar morphology. The convenient orientation of the system removes one source of uncertainty in modelling the structure, the inclination parameter. In addition, the high degree of symmetry in the nebulosity makes it possible to use axisymmetric models to investigate the envelope density profile and the shape of the bipolar cavity. This system is therefore an excellent site for investigating the generic properties of class I sources, before attempting to understand less symmetric systems. We do not believe that the quadrupolar morphology shows the system to be physically unusual, since it arises because the outflow lies in the plane of the sky and some of the ejected matter lies at the right distance to produce the extinction effect. High-resolution imaging of several young stellar objects (YSOs) in the Taurus cloud [LR1; Lucas & Roche 1998, hereafter LR2 (Paper II, this issue)] has shown that class I YSOs commonly display dusty outflows in their bipolar cavities.

One surprising attribute of the images in LR1 is that the relative brightness of the four flux peaks had changed over the 10-month period between the two epochs of observation in 1995. Specifically one of the peaks had brightened in the J, H and K bands, the increase being greatest at J band (≈ 57 per cent). We attributed this change to motion of circumstellar matter, which alters the illumination of the cavity walls. In this paper we present further observations in the broad-band filters which were undertaken to investigate the variability. Narrow-band H$_2$ and continuum images were also obtained in an attempt to resolve structure in the molecular outflow and distinguish line emission from reflection nebulosity.

2 OBSERVATIONS
Imaging was carried out with IRCAM 3 at the United Kingdom Infrared Telescope (UKIRT) through the UKIRT Service Programme in 1997 August–September. The observers were John Davies and Stuart Ryder for the JHK data (August 28) and narrow-band data (September 1); the L' data were obtained by Sandy Legget on September 24. IRCAM 3 has a 256 × 256 InSb array which is sensitive between 1 and 5.5 μm. A warm magnifier was employed to produce an image scale of 0.143 arcsec pixel$^{-1}$ in all the filters. At L' the source was also observed without the magnifier (0.286 arcsec pixel$^{-1}$) in order to reduce the thermal background. The broad filters used were J (1.25 μm), H (1.65 μm), K (2.2 μm) and L' (3.5–4.1 μm). Integration times were 540 s in each of the J, H and K filters. Some L' data had to be discarded.

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because of stripes of noise on the array caused by the rapid readout rate. After discarding bad data the $L'$ integration times were 480 and 288 s with and without the magnifier respectively. Narrow-band images were obtained with the H$_2$ (1–0) S(1) filter (2.122 μm) and adjacent continuum filter (2.104 μm) for which $\Delta \lambda / \lambda \approx 0.01$. The exposure times were 900 s in each filter, with the integrations in the two filters alternating in six groups of 300 s to minimize photometric errors arising from changes in a thin cloud layer that was present. Seeing conditions were photometric for the broad-band observations. The data were reduced with IRAF, using flat fields obtained from offset sky images. The H-band flat field had a low-level gradient, which reduced the sensitivity to extended nebulosity; this defect was partially remedied with a one-dimensional fitting task. The gradient is too small to affect the relative photometry of the flux peaks because of their small spatial separation. Individual frames were registered with respect to the equatorial dark lane for

![Figure 1. Broad-band images: (a) J band; (b) H band; (c) K band; (d) K band showing the extended structure of the outflow; (e) $L'$, no magnifier; (f) $L'$ with magnifier and Gaussian-smoothed ($\sigma = 1$ pixel) to reduce noise. Two faint stars ($m_K \approx 19$) are seen near the edge of the image mosaic in (d); these are denoted S1 and S2. Scale: the bar represents 200 au on the field. Contour levels are irregularly spaced to enhance structure, normalized to the peak. Levels: (a) 0.02(4), 0.03(4), 0.04(4), 0.06(2), 0.08(2), 0.10(2), 0.15, 0.2–0.9 with interval of 0.1. (b) 0.015(3), 0.02(3), 0.03(2), 0.04(2), 0.06(2), 0.08, 0.10(2), 0.15, 0.2, 0.3, 0.4, 0.5, 0.59, 0.7, 0.8, 0.9. (c) 0.01(4), 0.015(4), 0.02(4), 0.03(2), 0.04(2), 0.06(2), 0.08(2), 0.10(2), 0.15, 0.2, 0.3, 0.4, 0.5, 0.65, 0.8 0.9. (d) 0.005(6), 0.01(6), 0.015(4) and as (c) up to 0.10. (e) 0.2–0.9 with interval of 0.1. (f) 0.4–0.9 with interval of 0.1. Numbers in parentheses indicate data averaging in $n \times n$ pixel blocks.](https://academic.oup.com/mnras/article-abstract/299/3/723/1070556)
RA, and using the centroid of either peak P3 or peak P1 for declination. This was accurate to $\approx \pm 0.5$ pixels for most of the filters, which was quite sufficient in the prevailing seeing conditions. The registration in declination was less precise at $L'$ because of low signal-to-noise ratio. However, the core structure in the co-added images is not more extended than in the other filters, so it appears that no significant errors were introduced.

The tip/tilt secondary mirror of UKIRT was employed, using a reference star located 90 arcsec from IRAS 04302+2247 (HST GSC_01829_00916). The positional offset was too great for any significant adaptive gain in the $J$, $H$ and $K$ images but there was a useful improvement at $L'$. The $L'$ images of a stellar standard (HST GSC_01829_00875), which is offset by a similar distance from the guide star, showed an approximately elliptical point spread function (PSF), which is expected when observing near the edge of the isokinetic patch. We infer that IRAS 04302+2247 was observed with a similar 0.60 arcsec $\times$ 0.36 arcsec beam, elongated along the radial direction from the reference star (PA = 52°). The unmagnified image is therefore significantly undersampled but has a higher signal-to-noise ratio (10.9$\sigma$ at peak) than the magnified image ($\sim 5.5\sigma$ maximum). Owing to these low signal-to-noise ratios and the difficulty in reconstructing the azimuthal structure of the PSF, we do not attempt image deconvolution. We estimate that the resolution of the $JHK$ images was $\sim 0.8$ arcsec, slightly worse than our previous high-resolution data for this source (LR1). Regrettably, $JHK$ images of a stellar standard were saturated owing to the large optical–infrared colour index in the L1536 cloud, so we have absolute photometry only at $L'$ and in the narrow-band 2.1 $\mu$m continuum filter.

3 DATA

The broad-band images of 04302+2247 are shown in Fig. 1. The quadrupolar structure is just resolved in the $J$, $H$ and $K$ filters while at $L'$ the structure is tripolar. The improved signal-to-noise ratio of this $L'$ dataset compared to the data in LR1 reveals the underlying symmetry of the envelope. In the $J$ and $H$ bands peak P4 is barely detected, which we attribute to the greater extinction by dust in the cavity at shorter wavelengths. Even at $K$ band the system appears point-symmetric about a location close to the northern end of the equatorial dust lane. At $L'$ we see that the envelope extends well to the north of the narrowest point of the dust lane. The low-resolution $L'$ image (Fig. 1e) shows a highly symmetric bipolar nebula. In the high-resolution image (which has been Gaussian-smoothed to reduce the noise) the eastern lobe of the envelope is divided into two flux peaks but the western lobe is not so divided. The division into two peaks is attributed to extinction by a dusty outflow, which is seen extending to the east in Fig. 1(d), as described in Section 1.

Figure 2. $H_2$ data: (a) $H_2$; (b) 2.1 $\mu$m continuum, normalized to the same peak intensity. The regions of $H_2$ excess are indicated. Scale: the bar represents 200 au on the field. Contour levels are normalized to the peak: 0.04(2), 0.06(2), 0.08(2), 0.10(2), 0.15, 0.2–0.9 with interval of 0.1. Numbers in parentheses indicate data averaging in $n \times n$ pixel blocks.

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absence of such a division in the western lobe at $L'$ implies a lower optical depth in that part of the outflow. This is consistent with the absence of extended reflection nebulosity along the outflow axis to the west of the core. The apparent connection between the eastern and western lobes in the high-resolution image is an artefact of the smoothing.

In the $H_2$ image (Fig. 2a) the outflow is detected in line emission on both sides of the equatorial plane. On the east side the nebulosity appears more extended in $H_2$ than in the continuum. There is a statistically significant excess at a level of 5.5σ. Similarly, on the west side a thin stream of line emission is seen extending from the south-west corner of the core, well offset from the axis of the bipolar cavity. We do not show an $H_2$-continuum plot because this increases the noise and does not enhance the faint outflow structure. A south-western extension of the core is also seen in reflection in the broad-band data, but this is not coincident with the $H_2$ excess and may be part of the cavity wall. The western half of the outflow is split into at least three sections: the south-western component observed here; a north-western component observed by Gomez, Whitney & Kenyon (1997) as a well-collimated line of [S II] emission knots (HH394) extending up to 4 arcmin from the central source; and a faint western component located near the rotation axis approximately 30 arcsec west of the core, which is seen in $I$-band WFPC2 images from the *HST* archive (data obtained for S. Kenyon). A fourth component is presumed to be responsible for dividing the western lobe of the core into two flux peaks. The [S II] emission lies along a PA of 335°. If we take the rotation axis of the system to be perpendicular to the equatorial plane, then this is offset by ≈70° from the rotation axis. It seems likely that this is a projection effect since an outflow in that direction would have to pass through the circumstellar envelope. Even so, the [S II] emission must be highly inclined to the rotation axis, and it is clear that the bipolar outflow in this system is spread over a wide range of opening angles, so the good collimation of HH394 is somewhat peculiar. Optical jets are often associated with poorly collimated molecular outflows but in this system there appear to be several discrete streams. Since no emission along a PA of 335° is detected within 1 arcmin of the core in [S II], nor within the 30 arcsec radius of our near-infrared data, it is possible that the efficiency of collimation varies over time and the outflow has now entered a poorly collimated phase.

### Table 1. Peak fluxes.

<table>
<thead>
<tr>
<th>Filter</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
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<td>0.76</td>
<td>0.66</td>
</tr>
<tr>
<td>$H$</td>
<td>1.00</td>
<td>0.83</td>
<td>0.94</td>
<td>0.53</td>
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<td>0.88</td>
<td>1.05</td>
<td>≤0.3</td>
</tr>
<tr>
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<td>1.00</td>
<td>0.82</td>
<td>0.94</td>
<td>0.90</td>
</tr>
<tr>
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<td>0.87</td>
<td>1.25</td>
<td>≤0.5</td>
</tr>
<tr>
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<td>0.95</td>
<td>1.62</td>
<td>≤0.3</td>
</tr>
<tr>
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<td>1.00</td>
<td>0.74</td>
<td>1.03</td>
<td>0.89</td>
</tr>
<tr>
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<td>0.82</td>
<td>1.29</td>
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</tr>
<tr>
<td>$J$</td>
<td>1.00</td>
<td>0.95</td>
<td>1.47</td>
<td>≤0.3</td>
</tr>
</tbody>
</table>

Note: Fluxes are summed over a 1 arcsec aperture. Data from 1995 November are at lower spatial resolution, introducing apparent changes of ≈5 per cent from the 1995 January data in peaks P1 to P3. P3 brightened between 1995 January and November, with a larger change at shorter wavelengths, but shows little further change in the 1997 data. An increase in brightness of P4 at $K$ band is confirmed in the 1997 data, indicating a general increase in prominence of the eastern lobe of the nebula.

High-resolution CO mapping at millimetre wavelengths would make it possible to investigate the relationship between the driving jets and swept-up molecular gas and make a three-dimensional map of the outflow.

We performed relative photometry of the flux peaks to investigate the variability reported by LR1, see Table 1. The data sets from 1995 January and 1997 September are of sufficiently similar resolution that they can be directly compared. We confirm that peak P3 has increased in prominence since the first epoch, with a greater increase at shorter wavelengths. P4 has also brightened at $K$ band, which was previously unclear. This indicates a general brightening of the eastern lobe of nebulosity since 1995 January. There has been no clear change in peak brightness or the apparent envelope structure since the second epoch in 1995 November. Changes in the prominence of P3 at $J$ and $K$ in 1997 September are only slightly greater than the ≈5 per cent noise level. Smoothing of the 1995 January data indicates that the reduced contrast of the flux peaks in the 1997 September data can be attributed simply to the slightly lower resolution. Absolute photometry at $L'$ and at 2.1 μm yields magnitudes of $M_L = 10.3$ (7 arcsec diameter aperture) and $M_J = 11.2$ (12 arcsec aperture), which are in good agreement with values previously published by Kenyon et al. (1990).

### 4 DISCUSSION

The new data are consistent with the model developed in LR1 and LR2 using Monte Carlo simulations, in which the envelope has an $r^{-1.5}$ density profile from the cavity walls outward, modified by an exponential turn-down at the edge of the system, and some concentration of matter towards the equatorial plane. Our interpretation of the quadrupolar structure in terms of extinction by a dusty outflow in the bipolar cavity still appears to be correct, although, as expected, the outflow structure is shown to be more complex than the simple continuous optically thick bar used in the model. Only a low level of $H_2$ (1–0) S(1) flux is seen in the molecular outflow, so the degree of polarization that was measured in LR1 would not be significantly affected by it. The width of the equatorial dust lane in the broad-band filters is unchanged from the 1995 January measurements, and indicates that the near-infrared extinction law for circumstellar dust is considerably shallower than that measured in the interstellar medium, as discussed in LR2. This requires the presence of relatively large grains ($2\pi a/\lambda \geq 1$ at 2.2 μm).

Motion of dusty knots in the outflow remains the simplest explanation of the variability of the flux peaks. Although Herbig–Haro flows usually contain some high-velocity gas with speeds of ~200 km s$^{-1}$, e.g. Mundt et al. (1990), the bulk of the gas has a speed of only a few km s$^{-1}$ (see Moriarty-Schieven et al. 1992). This corresponds to a transverse motion of ~1 au yr$^{-1}$. It is therefore difficult to predict the time-scale on which future variations might occur.

The symmetry of the envelope, as shown by the $L'$ data, invites study at higher spatial resolution in the near-infrared. High-resolution imaging and astrometry would allow us to identify and track the motion of individual features in the bipolar outflow. Otherwise, only a long-term study is likely to uncover the cause of the variability.

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