The structure of molecular gas associated with NGC 2264: wide-field $^{12}$CO and H$_2$ imaging

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ABSTRACT

We present wide-field, high-resolution imaging observations in $^{12}$CO 3 → 2 and H$_2$ 1–0 S(1) towards a ~1 deg$^2$ region of NGC 2264. We identify 46 H$_2$ emission objects, of which 35 are new discoveries. We characterize several cores as protostellar, reducing the previously observed ratio of pre-stellar/protostellar cores in the NGC 2264 clusters. The length of H$_2$ jets increases the previously reported spatial extent of the clusters. In each cluster, <0.5 per cent of cloud material has been perturbed by outflow activity. A principal component analysis of the $^{12}$CO data suggests that turbulence is driven on scales >2.6 pc, which is larger than the extent of the outflows. We obtain an exponent $\alpha = 0.74$ for the size-linewidth relation, possibly due to the high surface density of NGC 2264. In this very active, mixed-mass star-forming region, our observations suggest that protostellar outflow activity is not injecting energy and momentum on a large enough scale to be the dominant source of turbulence.

Key words: stars: formation – ISM: jets and outflows – infrared: ISM – submillimetre: ISM.

1 INTRODUCTION

Studies of young clusters are essential for understanding star formation, since most stars, and especially massive stars, are known to form in clusters (Zinnecker & Yorke 2007). NGC 2264 is an attractive target for studying this mode of star formation, since it is nearby, has relatively low foreground extinction and there is a large population of pre-main-sequence stars, whose age spread is evidence of sequential star formation (Adams, Strom & Strom 1983). The region contains a wealth of submillimetre (submm) cores (Ward-Thompson et al. 2000), pre-main-sequence stars and protostellar sources (Teixeira et al. 2006; Young et al. 2006), many of which have formed in clusters (Wolf-Chase et al. 2003; Fűrész et al. 2006; Young et al. 2006). At 760–900 pc distance (see Baxter et al. 2009, and references therein for discussion), the region contains over 300 Class II objects and 30 Class I objects (Dahm & Simon 2005). Several young Class 0 objects have been identified (Fűrész et al. 2006; Peretto, André & Belloche 2006; Teixeira et al. 2006). Kinematic motions include large-scale infall motions (Williams & Garland 2002; Peretto et al. 2006), and large, fast outflows, including the well-known NGC 2264 G (Lada & Fich 1996; Hedden et al. 2006). The wide-field optical images of Reipurth et al. (2004) reveal a number of Herbig–Haro (HH) objects, several of which trace giant, parsec-scale outflows. Published infrared (IR) images of the NGC 2264 region cover only very small areas; maps of the NGC 2264 G molecular outflow (MHO 1358/1359; Davis et al. 2010) have been presented by Davis & Eisloffel (1995), while more recently a number of H$_2$ features (MHO 1349–1359) have been identified around NGC 2264 C by Wang et al. (2002).

Outflows have a significant impact on material within the parent molecular cloud, injecting energy and momentum at large distances. The outflows extend typically over 0.1–1 pc, and the combined subarcsecond-resolution H$_2$ images with deep spectral imaging in $^{12}$CO result in a more complete census of star formation activity in clustered regions. Outflow kinetic energies can be comparable to, or even larger than, turbulent and gravitational energies of natal clouds, and could have a significant disruptive effect (McKee & Ostriker 2007). In order to find evidence, and quantify the disruptive effects of molecular outflows, it is crucial to map the entire cloud.

Fig. 1 shows the Digitized Sky Survey (DSS) optical image of NGC 2264, with the main star formation regions and nebulae labelled, obtained with Starlink Gaia using Skycat. A detailed review of this region has been published by Dahm (2008). We present wide-field, high-resolution mapping observations of NGC 2264. Through CO observations we can provide a complete census of outflow activity in the region, investigating any dynamic impact the outflows are having on the parent molecular cloud through energy injection.

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http://archive.eso.org/cms/tools-documentation/skycat
Using $H_2$ narrow-line imaging, we can detect the youngest flows, from emission arising in gas shocked by the impact of protostellar outflows, and measure the extent of these flows by tracing the detected emission knots and HH objects.

2 DESCRIPTION OF OBSERVATIONS

2.1 Spectral line observations

The spectral line observations were taken at the James Clerk Maxwell Telescope (JCMT) using Heterodyne Array Receiver Programme (HARP; Buckle et al. 2009). Observations of CO $3 \rightarrow 2$ at 345.796 GHz were taken with a 0.488 MHz (0.423 km s$^{-1}$) spectral resolution and gridded with 6 arcsec spatial pixels. The beam size is 14 arcsec at 345 GHz. The map covers an area of 1 deg$^2$, and observations totalling 12.9 h were taken during 2007 August and October, in position-switch raster mode. The observations were taken in Band 3 weather, with zenith opacity values between 0.13 and 0.19, and average system temperatures $\sim$550 K. Averaged over emission-free regions of the map, a 1σ rms of 0.32 K pixel$^{-1}$ in 1.0 km s$^{-1}$ spectral channels was obtained.

All intensities reported here are in units of $T_A^*$, the antenna temperature corrected for sky and telescope losses (Kutner & Ulich 1981). The main beam brightness temperature $T_{mb} = T_A^*/\eta_{mb}$, with a main beam efficiency $\eta_{mb} = 0.66$. Frequent pointing and focus observations were carried out, and calibration observations were performed using N2071IR. The scatter in these observations suggest a calibration accuracy of $\sim$20 per cent.

The data were reduced and analysed using the Starlink project software, in particular SMURF (Jenness et al. 2008) and KAPPA (Currie et al. 2008) routines.

2.2 $H_2$ imaging observations

The IR imaging observations were taken at the United Kingdom Infrared Telescope (UKIRT) using the near-IR wide-field camera (WFCAM) (Casali et al. 2007). The observations cover an area on the sky of 0.75 deg$^2$ (a WFCAM ‘tile’), with a pixel size of 0.2 arcsec. Images were obtained through broad-band $K$ ($\lambda = 2.20$ µm, $\delta \lambda = 0.34$ µm) and narrow-band $H_2$ ($\lambda = 2.121$ µm, $\delta \lambda = 0.021$ µm) filters. Exposure times of 5 and 40 s were used; thus, the total per-pixel integration times were 100 and 800 s in $K$ and $H_2$, respectively.

Data were initially reduced by the Cambridge Astronomical Survey Unit (CASU), and distributed through the Wide Field Astronomy Unit (WFAU) archive. Further data reduction and analysis was carried out using Starlink KAPPA routines (Davis et al. 2009).

2.3 Data summary

The two data sets presented here probe the most active regions of current star formation. CO $3 \rightarrow 2$ emission traces dense, warm gas typical in regions of star formation, with temperatures 10–50 K and gas densities of $10^4$–$10^5$ cm$^{-3}$. The higher critical density of the $3 \rightarrow 2$ line over lower excitation lines makes this transition a useful tool for tracing dense, more collimated flows from the youngest sources. The rovibrational $H_2$ $1 \rightarrow 0$ S(1) line at 2.122 µm arises in regions with temperatures $\sim$2000–4000 K and densities $10^3$–$10^4$ cm$^{-3}$. Emission from this line indicates the presence of deeply embedded driving sources, and traces the youngest outflows.

Fig. 2 shows the integrated intensity map of CO $3 \rightarrow 2$ emission, in the velocity range $-20$ to $30$ km s$^{-1}$ (note all velocities are local standard of rest unless otherwise stated). The brightest integrated emission (246 K km s$^{-1}$) is towards the cluster NGC 2264 C, while the brightest peak intensity (28 K) is towards the head of the Cone Nebula. Filaments can be seen extending south from NGC 2264 C, east and west from NGC 2264 D and north-west from the S Mon. S Mon is a massive (17.8 M$\odot$) young star, of spectral type 07V (Herrero et al. 1992), and the radiation pressure and wind from this star is likely to be heating and dynamically affecting nearby regions, such as the protostellar outflow source NGC 2264 G (Lada & Fich 1996; Teixeira et al. 2008). The two outflow lobes of NGC 2264 G can be seen to the north-east of S Mon. West of S Mon, and extending southwards, is a region of very weak emission, which we refer to...
as a cavity, surrounded by a ring or bubble of emission containing several Submillimetre Common-User Bolometer Array (SCUBA) dust cores.

Dust pillars and cometary clouds, harbouring young stellar objects (YSOs), are prevalent in *Spitzer* imaging of massive star-forming regions (Smith et al. 2010), where the emission is dominated by strong polycyclic aromatic hydrocarbon (PAH) features. The Cone Nebula resembles one of these cometary regions in CO emission. The structure of this emission suggests that molecular gas is being ablated, possibly by the action of the NGC 2264 C cluster, exposing star-forming cores. Redshifted and blueshifted $^{12}$CO emission and H$_2$ emission at the head of the Cone indicate ongoing star formation activity.

Fig. 3 shows a colour composite image of the H$_2$ 1–0 S(1) and $K$-band images of NGC 2264. Ellipses mark the MHOs we have detected. Inset images show zoomed versions of these data towards

$^2$ $K$- and H$_2$-band FITS data available from http://www.jach.hawaii.edu/UKIRT/TAP/.
two regions: the cluster NGC 2264 D and an isolated outflow to the south-east. H$_2$ line emission appears as turquoise in these images, which are shown in detail in Figs A1–A4. We detect 46 MHOs, of which 35 are new discoveries, and describe these in detail in Appendix A. We detect regions of multiple jets and bow shocks surrounding NGC 2264 C (extending further than seen by Wang et al. 2002), NGC 2264 D and NGC 2264 G (as seen by Reipurth et al. 2004). There are additional regions of jet activity to the east of NGC 2264 D, and in the south-east corner of the map. Towards the Fox Fur Nebula and the Cone Nebula, we see much larger scale arcs and filaments in H$_2$ emission.

Representative CO spectra and the intensity-weighted velocity map are shown in Fig. 4, highlighting the varying and complex velocity structure of this region. To the north, emission from the Fox Fur Nebula has narrow linewidths, and velocities $\geq 9$ km s$^{-1}$. The star-forming clusters and NGC 2264 G have extended line wings due to outflow activity. The clustered regions of star formation are kinematically distinct, with different cloud velocities, as has been previously noted (Peretto et al. 2006; Maury, Andrè & Li 2009). The Cone region and NGC 2264 C have velocities $\sim 7$ km s$^{-1}$, while NGC 2264 D has velocity $\sim 5$ km s$^{-1}$. Several regions show multiple velocity components, including the cavity south-east of S Mon, the Cone Nebula and NGC 2264 D.

Crutcher, Hartkopf & Giguere (1978) and Fűrész et al. (2006) identify distinct regions across NGC 2264 which are broadly in agreement with the velocity gradient and extent of the red, green and blue velocity regions in Fig. 4, respectively. Sung, Stauffer & Bessel (2009) identify and assign ages to distinct star-forming clusters using Spitzer data. The region surrounding S Mon, including NGC 2264 G, is aged 3.1 Myr. The Cone Nebula is at a younger age, due to the number of embedded sources. Peretto, Hennebelle & André (2007) calculate very young ages for the clusters NGC 2264 C and NGC 2264 D of $\sim 0.1$ Myr. We look at the regions of active star formation in more detail in the following section.

### 3 ACTIVE STAR-FORMING REGIONS

The wide-field $^{12}$CO $3 \rightarrow 2$ and H$_2$ 1–0 S(1) data can be used to provide a comprehensive quantitative analysis of the star formation activity across NGC 2264. Outflow and jet properties are expected to change as protostars evolve from the early accretion phase. The youngest objects, which are still accreting most of their final mass, are expected to have more powerful outflows, as measured from the CO momentum flux or jet luminosity (Bontemps et al. 1996; Arce & Sargent 2006; Caratti o Garatti et al. 2006). In the following analysis, we use CO $3 \rightarrow 2$ to estimate the total outflowing mass, and the energy and momentum injected into the ambient cloud. We use H$_2$ 1–0 S(1) to estimate the total H$_2$ luminosity in the jets, and place constraints on the impact of star formation activity on the ambient cloud.

For the emission in the outflow wings, we assume optically thin conditions, and calculate the total mass and energetics of molecular gas using emission from the $^{12}$CO $3 \rightarrow 2$ transition following Garden et al. (1991) and Buckle et al. (2010). Maury et al. (2009) examined the opacity in the line wings of $^{12}$CO using CO isotopologues towards the NGC 2264 C cluster, and found the emission to be optically thin outside of the central $\sim 10$ km s$^{-1}$ of the line profile. For the outflow contribution at low velocities, the optically thin assumption may not be correct, and the masses are then lower limits. Since we make no correction for the inclination angle of the outflows, the values for momentum and kinetic energy are lower limits. We use an excitation temperature of $T_{\text{ex}} = 20$ K in order to...
aid comparisons with previously published work (e.g. Lada & Fich 1996). The data are thresholded at the 3σ level.

Due to the NGC 2264 velocity field (shown in Fig. 4), care needs to be taken in assigning velocity limits for the high-velocity emission. We have taken the values from Peretto et al. (2006), who describe N2H+ observations, giving systemic velocities of 7.5 km s\(^{-1}\) for NGC 2264 C and 5.5 km s\(^{-1}\) for NGC 2264 D. For the high-velocity material, we use the velocity intervals ±5.0 to ±20 km s\(^{-1}\) on either side of the systemic velocity for each cluster. For other regions, the sources are sufficiently isolated for an estimate of the systemic velocity to be made from \(^{12}\)CO emission in areas adjacent to the molecular outflows. For NGC 2264 G, we use a systemic velocity of 5.0 km s\(^{-1}\), with ranges up to ±30 km s\(^{-1}\) from the systemic velocity. Emission from ambient material covers the red lobe at low velocities, and so we use a lower velocity of 2 km s\(^{-1}\) for the red lobe and −1 km s\(^{-1}\) for the blue lobe. For the protostar in the far south, IRAS 2, we adopt a systemic velocity of 7.8 km s\(^{-1}\), and velocity intervals of 2–10 km s\(^{-1}\) for the redshifted emission and −6 to −1 km s\(^{-1}\) for the blueshifted emission.

We have extracted H\(_2\) line emission fluxes from the H\(_2\) + continuum data after carrying out aperture photometry with background subtraction to calculate the calibrated integrated line flux. The H\(_2\) + continuum data are used rather than the continuum-subtracted data, since these do not add to the calibration uncertainties, and there are no deep negative components from an imperfect subtraction routine. Calibration was checked on stars in the field with known K-band magnitude, and is accurate to the 10 per cent level.

The quadruple transitions of H\(_2\) (known as O, Q and S branches) are the main cooling mechanism for shock-excited jets detected in the near-IR. The rovibrational transitions arising in the near-IR, including the H\(_2\) 1–0 S(1) transition, can be used to estimate the total molecular hydrogen luminosity (L\(_{H_2}\)) of the flow. Younger flows are expected to have more powerful outflows and higher values of L\(_{H_2}\).

The total H\(_2\) luminosity (L\(_{H_2}\)) can be calculated from the H\(_2\) 1–0 S(1) luminosity (L\(_{H_2,1}\)), with L\(_{H_2,1} \sim 10L_{H_2,12}\) (Caratti o Garatti et al. 2006), for typical H\(_2\) jet temperatures between 1500 and 2500 K. If emission from the jet arises in regions at higher temperatures, this method will underestimate L\(_{H_2}\) by factors up to 2.5. L\(_{H_2}\) will also be underestimated by up to an order of magnitude in regions of high extinction (A\(_K\) = 25). Caratti o Garatti et al. (2006) have used near-IR spectral line observations to calculate the temperature and extinction towards one of the flows in our data set, NGC 2264 G. Their values of T = 2100–2800 K and A\(_K\) = 3–8 mag suggest that L\(_{H_2} = 10L_{H_2,12}\) is a reliable estimate of L\(_{H_2}\) for this region.

Table 1 shows the mass, momentum and kinetic energies calculated for the redshifted and blueshifted CO 3 → 2 emission, and the H\(_2\) luminosities, towards each region. Individual MHOs included for each region are described in Appendix A. For the whole cloud, L\(_{H_2} = 1.1 L_{⊙}\), although this is a lower limit, since we have not taken extinction into account. The masses are lower limits, since they are dependent upon temperature and opacity. If the high-velocity emission is excited at temperatures >20 K, or the assumption of optically thin emission is not valid, then the masses will be increased. Additionally, it is not possible to entirely separate emission from outflowing gas from that of the ambient cloud.

Towards all of the active star-forming regions, we find more mass, momentum and energy in the redshifted material than in the blueshifted material. Maury et al. (2009) have examined the individual flows in NGC 2264 C using CO and isotopic data, and also find the redshifted material to contain more mass and momentum. Asymmetry in molecular outflows is relatively common in low-mass protostars, although no mechanism has so far been proposed for the brightening of the redshifted lobe.

### 3.1 The NGC 2264 protoclusters

NGC 2264 D is a more massive cluster than NGC 2264 C, with more protostellar sources, more mass and energy, and covering a larger area. Within the uncertainties, both clusters have similar H\(_2\) luminosities. Fig. 5 shows the redshifted and blueshifted CO emission contoured over the H\(_2\) image towards NGC 2264 C. The jets and outflows in the cluster can be seen extending past the Cone Nebula to the south. To the south-west of IRS 1 is a redshifted flow that contains the most high-velocity gas, with line wings detectable out to ~30 km s\(^{-1}\). We have described in detail the individual H\(_2\) objects and CO flows in Appendix A.

Peretto et al. (2006) identify four of the 12 NGC 2264 C cores as pre-stellar. As described in Appendix A, all four of these cores are spatially located within collimated redshifted and blueshifted CO emission, and compact knots of H\(_2\) emission. Additionally, three of the cores are coincident with Spitzer 24-μm sources. These data suggest that these four cores are young Class 0/I protostars. Sung et al. (2009) classify 17 24-μm sources as protostellar in NGC 2264 C.

Peretto et al. (2006) estimate the total gas mass in NGC 2264 C to be 1650 M\(_{⊙}\), compared to the 3 M\(_{⊙}\) we estimate to be entrained in the outflow. Although there are multiple energetic outflows in this cluster, only ~0.2 per cent of the molecular gas has been entrained by outflows, or affected by star formation activity. This is a lower limit, since it is dependent upon the opacity.

Fig. 6 shows redshifted and blueshifted CO emission contoured over the H\(_2\) image towards NGC 2264 D. The cluster extends further westwards than previously observed, with the discovery of new jets and molecular outflows spatially adjacent to this cluster. The redshifted emission contoured at the south-eastern edge of the map is from the NGC 2264 C cluster. The total gas mass is 1310 M\(_{⊙}\) in NGC 2264 D (Peretto et al. 2006), so the molecular outflows, entraining 5 M\(_{⊙}\), constitute a negligible fraction (~0.4 per cent) of the cluster mass. Although this is a lower limit, this result implies that the large number of outflows are not affecting the bulk of molecular material.
Sung et al. (2009) classify 44 sources as protostellar in NGC 2264 D. There are many overlapping CO outflows and H$_2$ jets, which we are unable to separate near the sources, making source identification difficult. Forbrich et al. (2010) identify three embedded YSOs as candidate massive YSOs using PAH emission. One of these, SSB 11829, is coincident with a $^{12}$CO bipolar molecular outflow, and MHO 1385, a bright knot and extended west-facing bow shock, indicating that the source is protostellar. A more detailed description of the individual H$_2$ objects and CO flows is given in Appendix A.

3.2 NGC 2264 G

The two outflow lobes of NGC 2264 G can be seen just to the northeast of S Mon in Fig. 2. The driving source (Gomez et al. 1994; Teixeira et al. 2008) has a mass, including the envelope, of 2–4 $M_\odot$. Teixeira et al. (2008) report Spitzer imaging of the protostellar jet, showing three changes in direction. Fig. 7 shows the red and blue contours for three different velocity ranges through the outflow lobes, overlaid on the H$_2$ emission from the protostellar jet. The CO...
The lack of H$_2$ emission from the molecular outflow follows the emission in the jet, including the changes in direction. There is a strong correlation between the structure of H$_2$ emission and high-velocity CO outflow lobes in the NGC 2264 G outflow. The extent of the H$_2$ emission matches the size of the CO lobes, and the H$_2$ intensity peaks are close to the peaks seen in the CO maps.

The total extent of the red outflow lobe is ~280 arcsec, or 1.1 pc (assuming 800 pc to NGC 2264), with the very high velocity gas (>35 km s$^{-1}$) extending further than the lower velocity gas. The low-velocity emission (6 km s$^{-1}$) traces a cavity, while the high-velocity emission (40 km s$^{-1}$) traces a collimated flow. The blue lobe has a small high-velocity extension, and the total extent of the blue outflow lobe seen is ~200 arcsec, or 0.8 pc. These figures are in agreement with those derived from CO 2 $\rightarrow$ 1 observations (Lada & Fich 1996). The difference in the highest velocity spatial extent between the red and blue lobes we detect in CO 3 $\rightarrow$ 2 may be merely the amount of material available for entrainment in the two directions. The red lobe in Fig. 7(a) suggests a wide opening angle, with the H$_2$ emission (MHO 1359) associated with the northern edge of the flow. The clumpy structure seen very clearly in our new images of MHO 1359 could result from shock fronts in the boundary layer between the flow and the ambient medium. The lack of H$_2$ emission along the southern edge of the flow lobe could simply be due to a lower ambient density, suggesting a gradient in the ambient density that increases to the north across this region. Alternatively, Teixeira et al. (2008) propose a slowly precessing jet, plus additional deflection, to explain the structure. The broad red lobe we detect may suggest a density gradient, rather than a precessing jet. Table 1 gives the calculated outflow parameters for the NGC 2264 outflow. The total mass entrained in the outflow is 0.9 M$_\odot$ with a momentum of 11 M$_\odot$ km s$^{-1}$. This is consistent with the mass and momentum found for the lower excitation CO 2 $\rightarrow$ 1 transition (1 M$_\odot$, 12 M$_\odot$ km s$^{-1}$; Lada & Fich 1996).

### 3.3 S Mon

S Mon is positioned in front of and travelling towards the NGC 2264 cloud (Tauber, Lis & Goldsmith 1993), affecting the region with an intense ionizing field. The emission surrounding S Mon shows many filaments and arcs, although the lack of extended line wings and H$_2$ knots suggests there is no protostellar outflow activity. The emission near S Mon is seen across a large velocity range, from 6.7 to 13.5 km s$^{-1}$, and is characterized by relatively small linewidths, indicating that the complex kinematic structure is not due to protostellar outflow activity. At the highest red and blue velocities, the emission is very clumpy and fragmented. In the ring of emission (Fig. 2), a cluster of SCUBA cores to the north-west is associated with CO clumps at blueshifted velocities, while the SCUBA cores to the south-east are associated with CO clumps at redshifted velocities.

### 3.4 NGC 2264 IRAS 2

Fig. 8 shows outflow lobes associated with a source first detected by Margulis, Lada & Young (1989). This is a far-IR source with no optical counterpart and no previously detected outflow, designated as IRAS 2, with a luminosity of 6.7 L$_\odot$. Wolf-Chase, Walker & Lada (1995) detected an extended CS source at this position, but no outflow. Along with a weak CO molecular outflow, we also detect H$_2$ knots indicating protostellar jet activity, in MHO 3109 (Fig. 8).

The outflow candidate NGC 2264 A (Margulis, Lada & Snell 1988) is ~400 arcsec east of IRAS 2. Although a red outflow lobe has previously been detected towards NGC 2264 A, we do not clearly detect the outflow lobe in CO 3 $\rightarrow$ 2 emission, or detect any H$_2$ emission.

### 3.5 IRAS 06396+0946

East of the main emission region, at the position RA = 06$^h$42$^m$25$^s$.5 and Dec. = 09$^\circ$43$^\prime$09$^\prime\prime$, is a cometary-shaped feature surrounded by
several small and compact regions in $^{12}$CO, which are blueshifted to the north-west and redshifted to the south-east. The peak antenna temperature is 10.8 K, and the lines are narrow with full width at half-maximum (FWHM) $\sim 1.0$ km s$^{-1}$ from a Gaussian fit to the data. Fig. 9 shows the integrated intensity image of this region, in the velocity range 10.1–13.9 km s$^{-1}$, along with the intensity-weighted velocity image that shows the velocity field. This is an intriguing structure, which could be associated with IRAS 06396+0946, although there are as yet no other published data on this region. The velocity field suggests an outflow or jet, although the morphology of the $^{12}$CO emission is more reminiscent of H$_2$ knots, such as those in the blueshifted jet of NGC 2264 G, rather than the more linear or elliptical structures more commonly seen in CO. There is no H$_2$ emission associated with this object. The spatial alignment and velocity structure of this region may just be coincidental, however, with the emission arising in areas at different distances which are not related. More sensitive observations would be required to determine whether these emission regions are connected.

### 3.6 The NGC 2264 D filament

To the east of NGC 2264 D, there are two newly detected MHOs, MHO 1378 and MHO 1379, shown in Appendix A (Fig. A1b). The location of the MHOs and the velocity structure of the CO emission suggest that these MHOs may be associated with molecular outflows that are erupting from the dense gas in the cluster, which contains several Spitzer-identified protostars (Sung et al. 2009). However, the line profiles do not have the line wings usually associated with molecular outflows. As the velocity increases from 1.0 km s$^{-1}$, two filaments extend eastwards from the bulk of the cluster, eventually overlapping and merging at velocities $\sim 5.0$–6.5 km s$^{-1}$, when the overall length is $\sim 11$ arcmin. At higher velocities the filament becomes more pronounced, with additional internal structure that is very linear. The brightest regions are those furthest from the central cluster.

### 4 PRINCIPAL COMPONENT ANALYSIS

In order to undertake an analysis of the turbulent characteristics of NGC 2264, we have carried out a principal component analysis (PCA) on the $^{12}$CO data. The method is relatively robust against the effects of resolution and noise. The low-order components contain features that contribute most to the variance of the data, while higher order components contain more subtle features within the spectral shapes.

We have implemented the technique described by Heyer & Schloerb (1997), Brunt & Heyer (2002a) and Brunt & Heyer (2002b) who detail the methods in full. This technique transforms the original spectroscopic data cube (RA, Dec. and velocity) into a set of orthogonal functions which are described by the principal components, $l_i$, ordered by decreasing variance of the data projected on to each orthogonal vector. The principal components consist of an eigenvector, tracing only the velocity structure, and an eigenimage, constructed from the projection of the data on to each of the eigenvectors. Each eigenimage therefore contains only spatial structure, mapping the size scales of differences in the line profiles traced by the eigenvectors. The principal components have characteristic length scales ($l_i$) determined from the eigenimage, and characteristic velocity scales ($\delta v_l$) determined from the eigenvectors. The eigenvectors and eigenimages of each principal component are coupled, so the physical dynamics can be determined from the characteristic scales. The data can be reconstructed from a linear combination of only the significant principal components, which account for most of the variance, or variability, in the data.

The technique provides an objective method of extracting the most significant components of the data for analysis, the challenge then being to interpret the results in a physically meaningful way. Brunt & Heyer (2002a) have carried out a PCA on simulated data in order to provide empirical relations between the derived PCA results and the statistics of the original data, which we utilize in this analysis to aid the physical interpretation.

Brunt, Heyer & Mac Low (2009) used numerical magnetohydrodynamic models and molecular spectral line observations to show that the ratio of the characteristic length scales of the first two principal components ($l_2/l_1$) is related to the ratio of the turbulent driving scale to cloud size ($\lambda_D/l_D$) for isotropically forced turbulence (see also Brunt 2003). Therefore, observational measures of $l_2/l_1$ can be used to estimate $\lambda_D/l_D$. For ratios $> 0.2$, there is little sensitivity to the actual driving scale, and large-scale driving best describes the turbulent driving scale (Brunt et al. 2009).

#### 4.1 Principal components

Following Brunt (2003), we do not subtract the mean from the data, so that $l_1$ approximates the integrated intensity and mean line profile of the $^{12}$CO data. The scale of data values in the eigenvectors is not directly related to flux, but to the contribution of the principal component to each velocity channel. Large relative positive or negative values indicate that a principal component contributes significantly in that velocity channel. The eigenimages can be used as a diagnostic of how much spatial structure is associated with each eigenvector.

### Table 2. Contribution of the first 10 principal components to the NGC 2264 CO data. Characteristic length and velocity scales for the five significant principal components are listed.

| $l$ | Variance (per cent) | Cumulative variance (per cent) | $l_2$ (pc) | $\delta v_l$ (km s$^{-1}$) |
|-----|---------------------|-------------------------------|------------|--------------------------|
| 1   | 74.15               | 74.15                         | 7.5        | 6.3                      |
| 2   | 20.86               | 95.01                         | 2.6        | 2.5                      |
| 3   | 3.16                | 98.18                         | 1.3        | 1.7                      |
| 4   | 0.73                | 98.90                         | 0.6        | 1.3                      |
| 5   | 0.51                | 99.41                         | 0.6        | 0.8                      |
| 6   | 0.21                | 99.63                         |            |                          |
| 7   | 0.08                | 99.71                         |            |                          |
| 8   | 0.05                | 99.76                         |            |                          |
| 9   | 0.03                | 99.79                         |            |                          |
| 10  | 0.02                | 99.82                         |            |                          |
Table 2 lists the first 10 principal components, along with the variance and the total cumulative variance for each component. The first five principal components contribute >99 per cent of the variance, with $l_1$ accounting for 74 per cent of the variation in the data. The largest values of $L_i$ correspond to the largest values of $\delta v_i$, indicating that the largest velocity differences are distributed on the largest scales.

Fig. 10 shows the eigenimages and eigenvectors associated with the first five principal components. The black and white (positive and negative) regions in the eigenimages trace velocity fluctuations.
whose magnitude is indicated by the width of features in the eigenvectors. The first principal component, \( I_1 \), as noted above, has an eigenimage which approximates the \(^{12}\)CO integrated intensity map. The centre velocity of the emission is 7.4 km s\(^{-1}\), and it has a large FWHM linewidth of 6.9 km s\(^{-1}\), from a Gaussian fit to the eigenvector, which approximates the mean line profile of the \(^{12}\)CO data. \( I_2 \) shows a positive–negative dipole pattern that is characteristic of giant molecular clouds (Brunt et al. 2009), when the turbulence is driven on scales comparable to the cloud size. The lower velocity contributes mostly to spatial variations in the north, while the higher velocity contributes mostly to spatial variations in the south. This is consistent with the velocity field we determined for NGC 2264, as discussed in Section 2.3. The positive velocity component of \( I_2 \) is at 5.4 km s\(^{-1}\), with a linewidth of 4.2 km s\(^{-1}\). This is spatially most closely associated with the emission from the star-forming clusters in the cloud, NGC 2264 C and NGC 2264 D. The negative velocity component of \( I_2 \) is at 10.4 km s\(^{-1}\), and has a narrower linewidth of 2.6 km s\(^{-1}\). This component is spatially most associated with emission from the region near S Mon, and the tip of the Cone. \( I_3 \), with peaks at 4.0, 8.2 and 10.9 km s\(^{-1}\), and linewidths of 2.9, 1.7 and 1.6 km s\(^{-1}\), describes velocity and linewidth variations within the velocity components identified in \( I_1 \) and \( I_2 \). All of the significant principal components also show an isolated, compact region of emission to the east of the main emission region, at the position associated with IRAS 06396+0946 (discussed in Section 3).

Further principal components describe successively smaller spatial variations in velocity and linewidths. By \( I_5 \), there is negligible emission in the eigenimages, and from these high-order principal components, noise estimates can be made (Brunt & Heyer 2002b).

### 4.2 Characteristic scales

Using results from the PCA decomposition, we can investigate the characteristic velocity variations and the spatial scales over which they occur. The characteristic scales are calculated using the normalized autocorrelation functions (ACFs) of each principal component, \( l \), following Brunt & Heyer (2002a). The spatial scales are calculated using noise-subtracted, resolution-corrected ACFs. Given the limited number of spectral pixels, the characteristic velocity scale measurements are largely unaffected by instrumental noise. Instrumental noise and finite resolution effects are explained in detail by Brunt & Heyer (2002a), whose procedures we have implemented. The characteristic velocity and length scales (\( \delta v_1 \) and \( L_1 \)) are determined from the lag at which the normalized ACFs of the eigenvectors and eigenimages fall to \( e^{-1} \), and are calculated following Heyer & Schloerb (1997).

The characteristic length scales \( L_1 \) and the characteristic velocity scales \( \delta v_1 \) for the five significant principal components are listed in Table 2. Both the length and velocity scales decrease with increasing \( l \). These scales can be visualized in the eigenimages and eigenvectors, where we can see, respectively, the spatial scale of variation and the width of spectral features, decreasing as \( l \) increases. The assumption of a PCA of molecular cloud spectral line data is that the decreasing size scales are reflecting a fundamental property of the kinematics of the gas within the cloud (Heyer & Schloerb 1997), from which turbulent driving scales (\( L_0 \)) can be determined. The longest flow we detect towards NGC 2264 is that of NGC 2264 G, at 280 arcsec, or 1.1 pc. Comparing this value with the \( L_0 \) size scales suggests that the outflows we detect are contributing to the variance in the data at characteristic scales \( < L_0 \), and so are contributing <3 per cent to the variance in the data. They are not, therefore, contributing at the size scales necessary to be the main component driving turbulence. This is supported by our analysis in Section 3, where we found that <0.5 per cent of the cluster masses have been entrained within molecular outflows.

On the largest scales, the velocity variations are due to differences between components that make up the entire molecular cloud. The characteristic spatial scale of the first eigenimage, \( L_1 = 7.5 \) pc, therefore gives an estimate of the overall cloud size, \( L_D \). The characteristic scale of the second eigenimage, \( L_2 = 2.6 \) pc, measures the size-scale over which the largest velocity variations occur in the data. \( L_2 = 2.6 \) pc can therefore be associated with the turbulent driving scale.

Carroll, Frank & Blackman (2010) have examined the use of PCA in simulations of outflow-driven turbulence, isotropically forced turbulence and a combination of both. They find that the ratio of characteristic length scales \( L_2/L_1 \) correctly identifies the largest driving scale in all three types of simulations, but suggest that the scales derived from PCA are measuring the largest scale of coherent motion, which is not necessarily the turbulent driving scale. As noted by Carroll et al. (2010), this distinction is important in clouds where outflows are present within an external cascade, or where there are large-scale coherent motions due to angular momentum conserving collapse. In our PCA, the principal components describe a large-scale velocity field across the cloud, with contributions from high-velocity outflow emission. As shown in Fig. 4, the velocity field of NGC 2264 shows little evidence for large-scale coherent motions. There is no indication of a rotation axis for the region as a whole.

We follow Brunt et al. (2009) and use the ratio of the characteristic length scales, \( L_2/L_1 \), to estimate the turbulent driving scale. From the ratio of the spatial scales of the first two eigenimages, we derive a fractional driving scale of 0.35, indicating large-scale driving. Combined with the characteristic scale \( L_2 = 2.6 \) pc associated with the turbulent driving scale, and our analysis in Section 3, these data indicate that protostellar outflow activity in NGC 2264 is not the dominant component of turbulence, even though it is a young and energetic star-forming region.

### 4.3 Size-linewidth correlation

Larson (1981) developed an empirical relation between the linewidth \( \Delta V \) and cloud size \( R \), with \( \Delta V \propto R^\alpha \) and \( \alpha = 0.5 \). This power-law relation is similar to that expected from studies of turbulence, where values of \( \alpha \) can range from \( \alpha = 1/3 \) for the incompressible energy cascade to \( \alpha = 1/2 \) for a shock-dominated turbulent fluid (McKee & Ostriker 2007, and references therein). The equivalent PCA velocity statistic \( \alpha \) is obtained from the set of significant \( \delta v_1-L_1 \) pairs which are larger than the resolution limits. These form the power-law relationship \( \delta V \propto L^\beta \). Brunt (2003) compared observations to simulations, and obtained values of \( \alpha \) from 0.5 to 0.8.

Brunt et al. (2003) relate the exponent of the characteristic velocity and length scale relation, \( \alpha \), to the scaling properties of the intrinsic velocity field. Roman-Duval et al. (2011) derive a PCA calibration for the exponent of the turbulent velocity spectrum \( E(k) \propto k^{-\beta} \), finding \( \beta = 0.2 \pm 0.05 + (2.99 \pm 0.09)\alpha \). Values of \( \beta < 5/3 \) are expected for the incompressible energy cascade model (Elmegreen & Scalo 2004, and references therein). Roman-Duval et al. (2011) applied their results to a sample of 367 molecular clouds, finding \( \langle \alpha \rangle = 0.61 \pm 0.2 \) and \( \langle \beta \rangle = 2.06 \pm 0.6 \).

We calculate \( \alpha = 0.74 \pm 0.08 \) and \( \beta = 2.4 \) from our PCA. The value of \( \alpha \) is larger than that expected from a classic linewidth-size relationship (Larson 1981) in giant molecular clouds, but is...
consistent with measurements towards the NGC 2264 C region (Maury et al. 2009) using observations of $^{13}$CO. The size–linewidth correlation is thought to depend upon the mean surface density of the cloud (Heyer et al. 2009), and so $\alpha$ values will be higher in regions of high surface density. NGC 2264 has a mean surface density $> 10$ times that assumed for the classic linewidth–size relation (Maury et al. 2009). $\alpha = 0.74$ is consistent with values found in high-mass star-forming regions such as the Rosette molecular cloud (Heyer, Williams & Brunt 2006).

The $\beta$ value of 2.4, giving $E(\lambda) \propto k^{-2.4}$, is larger than the values expected for Kolmogorov-type turbulence, but is similar to values found using $^{12}$CO towards Perseus (Sun et al. 2006), where values were higher in active star-forming regions than in dark clouds. A steep energy spectrum is consistent with the energetic star formation activity of NGC 2264.

5 SUMMARY

We have presented wide-field spectral imaging observations in $^{12}$CO 3 → 2 and wide-field high-resolution imaging observations in $^{13}$CO 1–0 S(1) towards NGC 2264. These observations, covering nearly 1 deg$^2$, offer a detailed view of the star formation activity taking place in this clustered environment. We find the following.

(i) Protostellar outflow activity in NGC 2264 does not occur on large enough scales to drive the turbulence. The largest flows extend to $\sim 1$ pc, while a PCA suggests that turbulence is driven on scales larger than 2.6 pc.

(ii) Only a small fraction, $< 0.5$ per cent, of the cluster gas mass in NGC 2264 C and NGC 2264 D has been swept up to high velocities through protostellar outflow activity. The outflow activity is not having a sufficient impact on the cloud to be the dominant source of turbulence.

(iii) We detect 46 molecular jets and knots in H$_2$, 35 of which are new detections. Based on the new H$_2$ data, NGC 2264 C and NGC 2264 D extend to a larger spatial extent than previously determined.

(iv) NGC 2264 D contains a larger mass of gas at higher velocities, and also more energy and momentum than NGC 2264 C.

(v) Due to the presence of spatially distinct redshifted and blueshifted CO emission, and H$_2$ emission in the form of jets or bow shocks, we characterize four cores in NGC 2264 C as protostellar that were previously identified as pre-stellar.

(vi) Of the three massive YSO candidates in the NGC 2264 D cluster, we detect a bipolar molecular outflow and H$_2$ jet towards SSB 11829.

The large number of protostars, jets and outflows in the NGC 2264 region, and their small separations, require very high resolution observations in order to isolate the flows and identify driving sources. This will be possible in future observational studies with the resolution and sensitivity offered by ALMA.

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APPENDIX A: PROTOSTELLAR JETS AND OUTFLOWS

A1 Molecular hydrogen emission-line objects

Table A1 lists the 46 MH0s identified in this work. Of these, MH0 1375–1399 and MH0 3100–3109 are new discoveries. Figs A1 and A2 show the H2 emission maps of the MH0s listed in Table A1. H2 emission maps of NGC 2264 C and NGC 2264 D are shown in the next section to aid visualization when discussing the clusters.

A2 The protostellar content of NGC 2264 C

NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards NGC 2264 C is associated with IRS 1, or Allen’s source, an early B star discovered by Allen (1972), who estimated extinction towards
CMMJ has been identified as pre-stellar by Peretto et al. (2006), but we see evidence of a chain of H$_2$ knots, MHO 1353, and weak redshifted emission associated with this source, perpendicular to the blueshifted outflow lobe from CMM1. Any blueshifted emission that may be associated with this source is entangled with the blue outflow lobe from CMM1. There is a knot 1–2 arcmin ESE of NGC 2264 C.

There are also two compact H$_2$ knots, MHO 1310, which align with the blueshifted lobe of CMM1. CMM10 is close to a Spitzer 24-µm Class I source (13288; Sung et al. 2009), very close to IRS 1, which is saturating the H$_2$ image.

The Spitzer peak is spatially most closely aligned with the red outflow lobe, and is close, although not coincident with CMM10. There are also two compact H$_2$ knots, MHO 3106, which align with this source and redshifted emission. Therefore, we tentatively identify CMM10 as the driving source of this flow. Any blueshifted emission is coincident with the energetic flows at the centre of the cluster, and not easily distinguishable.

CMM13 has a spectacular bipolar jet and molecular outflow, and has a particularly clear jet and multiple bow shocks, MHO 3107, associated with the blueshifted lobe. The redshifted lobe is coincident with MHO 1351.

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The remaining CMM sources are all tightly clustered near Allen’s source, which drives an energetic bipolar flow, and is saturated in the H$_2$ emission, making it difficult to establish individual flows.

A3 The protostellar content of NGC 2264 D

NGC 2264 D is less luminous than NGC 2264 C, forming several intermediate-/high-mass stars (Peretto et al. 2006) with core masses of 1.9–17.3 M$_\odot$, estimated from submm observations. The submm sources are less clustered than in NGC 2264 C, but high-resolution observations (Teixeira et al. 2006; Sung et al. 2009) show that many of the submm sources are coincident with multiple tightly clustered protostars. Forbrich et al. (2010) detect PAH emission surrounding three embedded YSOs in NGC 2264 D, making them candidate massive YSOs. We investigate the protostellar status of these objects using our CO and H$_2$ data. All of the candidates, SSB 10710, SSB 11829 and SSB 12820, are associated with compact K-band continuum sources. SSB 11829 is coincident with a $^{12}$CO
Wide-field imaging of NGC 2264

Figure A3. Top: H$_2$ colour composite image of NGC 2264 C, as in Fig. 3. Bottom: redshifted and blueshifted CO emission contoured over the H$_2$ continuum-subtracted grey-scale image. Contours are at 3.9, 6.5, 9.1, 14.3, 19.5, 27.3, 37.7 and 48.1 K km s$^{-1}$. Redshifted emission extends from 12.2 to 30.9 km s$^{-1}$, and the blueshifted from −17.8 to 2.1 km s$^{-1}$. The saturated source seen in the H$_2$ emission is Allen’s source (Allen 1972). The sources identified by Peretto et al. (2006) are marked and labelled with the CMM number.

bipolar molecular outflow, and MHO 1385, a bright knot and extended west-facing bow shock, indicating that the source is protostellar. A second, SSB 10710, has a very faint H$_2$ emission knot to the west, although this is not a sufficiently significant detection to be identified as an MHO, and we do not detect any clear outflow signatures in $^{12}$CO that we can identify with this source.

11 pre-stellar and four protostellar cores have been identified by Peretto et al. (2006), and we have adopted their labelling scheme of labelling the cores DMM1–DMM15. Fig. A4 shows the redshifted and blueshifted contours overlaid on the H$_2$ emission, as in Fig. 6, with the DMM sources also labelled. Six of the pre-stellar cores are coincident with Spitzer 24-$\mu$m identified protostars (Sung et al. 2009), and two of these show clear outflow structure in CO emission, DMM2 and DMM13. Both of these are part of a ridge containing a previously identified protostellar source, DMM7. The final source in this ridge, DMM15, is also associated with a 24-$\mu$m source, but only has weak evidence of outflow activity. The NGC 2264 D cluster is more tightly clustered than NGC 2264 C, and many of the DMM
Figure A4. Top: H$_2$ colour composite of NGC 2264 D, as in Fig. 3. Bottom: redshifted and blueshifted CO emission contoured over the H$_2$ continuum-subtracted grey-scale image. Contours are at 3.9, 6.5, 9.1, 14.3, 19.5, 27.3, 37.7 and 48.1 K km s$^{-1}$. Redshifted emission extends from 11.1 to 25.5 km s$^{-1}$, and the blueshifted from −18.5 to 1.0 km s$^{-1}$. The sources identified by Peretto et al. (2006) are marked and labelled with the DMM number.

sources are colocated with multiple Spitzer-identified protostars, making it difficult to isolate individual flows. Where this has been possible, we list in Table A3 the CO outflows and MHOs we have been able to associate with a driving source, and the lengths of the flows measured from either the H$_2$ emission or from CO redshifted or blueshifted emission. We describe the flows in more detail below.

The area surrounding MHO 1385 contains two pre-stellar cores, DMM4 and DMM6, and four Spitzer-identified protostars (Sung et al. 2009), one of which is coincident with an H$_2$ knot. MHO 1385 is associated with mainly blueshifted emission, with a more compact, slightly overlapping redshifted CO flow to the west. Although there are multiple sources in this region, the bipolar flow is not obviously associated with any of the nearby sources or H$_2$ emission. Midway between DMM4 and DMM6 lies a candidate massive YSO, SSB 11829 (Smith et al. 2010), and it is this source that is spatially aligned with the molecular outflow and MHO 1385. 50 arcsec to the south-east of MHO 1385 are two more H$_2$ objects, MHO 1383 and MHO 1384, two pre-stellar cores, DMM2 and DMM15, and
Table A2. Driving source identifications for NGC 2264 C flows.

| Source   | H$_2$ CO lobes | Length (arcsec) |
|----------|----------------|-----------------|
|          | Red Blue       | Red Blue        |
| CMM1     | MHO 1352 Y Y   | 45 58           |
| CMM2     | MHO 1304 Y Y   | 92              |
| CMM3     | MHO 1356 Y ?   | 75              |
| CMM6     | MHO 1355 Y Y   | 67 14           |
| CMM7     | MHO 3108 MHO 1354 Y Y | 90 100 |
| CMM8     | ? ? Y Y       | 31 20           |
| CMM9     | MHO 1353 Y ?   | 77              |
| CMM10/13288$^a$ | MHO 3106 Y ? |                  |
| CMM13    | MHO 1351 MHO 1350 Y Y | 126 124 |
| 13350$^a$ | MHO 1303 Y N | 41 46           |
| 14314$^a$/14415$^a$ | MHO 1357 Y ? |                  |

$^a$Identification from Sung et al. (2009).

Table A3. Driving source identifications for NGC 2264 D flows.

| Source   | H$_2$ CO lobes | Length (arcsec) |
|----------|----------------|-----------------|
|          | Red Blue       | Red Blue        |
| DMM7     | MHO 1386 Y ?   | 45              |
| –        | MHO 1380 MHO 1381 Y Y | 42 17 |
| –        | MHO 1382 Y     | 66              |
| –        | MHO 3100 Y Y   | 35 52           |
| 12253$^a$ | MHO 1377 N Y | 19              |

$^a$Identification from Sung et al. (2009).

MHO 1380 is coincident with a compact peak of redshifted CO emission. MHO 1381 is associated with weak blueshifted emission, and could be a counterpart. There is no known source associated with this flow, or with MHO 1382, which ends in a bright, knotty arc of emission. The shape of the arc suggests that it is driving towards the cluster, not away from it. MHO 1382 is associated with an extended redshifted flow, with no detectable driving source. MHO 1391 contains multiple arcs and knots of H$_2$ emission; each of the H$_2$ clusters is associated with a peak of redshifted CO emission – four in total. At the southern end of MHO 1391, there is a compact blueshifted emission region that overlaps the penultimate redshifted region. However, there is no source that is obviously driving these flows. There are no detected sources at the southern end of MHO 1391, although there is a pre-stellar core, DMM8, to the north, and seven Spitzer-identified protostars to the north-east, near DMM1. DMM1, located within 8 arcsec of five Spitzer-identified protostars, is also coincident with MHO 1388.

MHO 1392 is part of the dominant region of redshifted emission that extends across ~8 arcmin to the south-west of NGC 2264 D. It is crossed by a double-peaked region of blueshifted emission, although there is no nearby source detected that could be driving this flow. MHO 1393, MHO 1395 and MHO 1394 are also coincident with this long ridge of redshifted emission, although the different alignments of the knots, jets and bow shocks associated with these MHOs indicate that they may be arising in smaller flows that we are not able to distinguish from the larger scale flow. Further along the large redshifted flow are several more MHOs, MHO 1397, MHO 1398 and MHO 1399, each of which is coincident with peaks in the redshifted flow. At the south-west tail of the large red flow is a compact bipolar flow that has MHO 3100 associated with the redshifted lobe. There is no detected driving source for this flow, but it does lie outside the SCUBA and Spitzer-observed areas. To the north of NGC 2264 D, MHO 1377 is coincident with a weak compact clump of blueshifted emission, and a Spitzer-identified protostar, 12253 (Sung et al. 2009).

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