The JCMT Legacy Survey of the Gould Belt: a first look at Serpens with HARP

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ABSTRACT

The Gould Belt Legacy Survey (GBS) on the JCMT has observed a region of 260 square arcminutes in $^{12}$CO $J=3\rightarrow2$ emission, and a 190 square arcminute subset of this in $^{13}$CO and C$^{18}$O towards the Serpens molecular cloud. We examine the global velocity structure of the non-outflowing gas, and calculate excitation temperatures and opacities. The large scale mass and energetics of the region are evaluated, with special consideration for high velocity gas. We find the cloud to have a mass of 203 M$_\odot$, and to be gravitationally bound, and that the kinetic energy of the outflowing gas is approximately seventy percent of the turbulent kinetic energy of the cloud. We identify compact outflows towards some of the submillimetre Class 0/I sources in the region.

Key words: stars: formation – molecular data – ISM: kinematics and dynamics – submillimetre – ISM: jets and outflows

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1 INTRODUCTION

1.1 The JCMT Gould Belt Survey

The James Clerk Maxwell Telescope’s (JCMT) Gould Belt Legacy Survey (Ward-Thompson et al. 2007) is a large scale programme to observe nearby (<500 pc) regions of active star formation in both submillimetre continuum emission and three CO species J = 3 → 2 emission. The survey will observe molecular clouds with SCUBA-2 (Holland et al. 2006) to detect the continuum emission, and has been carrying out heterodyne spectrometer observations of filamentary regions in a subset of these clouds. These observations are currently being carried out with HARP/ACIS (Buckle et al. 2009) in the 12CO, 13CO and C18O isotopologues, in the J = 3 → 2 transition. POL-2 (Bastien et al. 2005), the SCUBA-2 polarimeter, will also be used to study some of the SCUBA-2 observed regions. A first look at the data from the Orion-B region has already been presented, by Buckle et al. (2010), and from the Taurus region by Davis et al. (2010).

The survey seeks to perform some of the first large scale analyses of very large, high resolution submillimetre maps and data cubes of the closest molecular clouds and examine the star formation occurring within them. In particular, the spectral part of this survey will examine the properties of higher density gas than most large scale surveys, due to the higher critical density of the J = 3 → 2 transitions (10^4 – 10^5 cm^-3). This is better matched to the densities probed in submillimetre continuum emission than the lower J transitions. The aims of the spectral survey are to search for and categorise high velocity outflows in order to identify protostars; to examine the column density in cores; to study the support mechanisms of protostars and their evolution; and to examine the turbulence and velocity structure of the parent molecular clouds (Ward-Thompson et al. 2007). SCUBA-2 continuum observations will also be made, and will cover an extremely large area compared to the current data sets available from e.g. SCUBA. As well as looking at the individual regions, the GBS will carry out statistical studies and comparisons on all the data sets and objects found.

1.2 The Serpens molecular cloud

The Serpens molecular cloud is a much-studied region of low mass star formation, located ~230 pc from the Sun (Eiroa et al. 2008) and references therein, in particular Straizys et al. (2003). It is forming a compact and high density cluster of new stars, and its close proximity allows us to map its gas properties at high spatial resolution (a FWHM beam size of 3300 AU at the distance of Serpens for 12CO). The cloud consists of two clusters of embedded YSOs of which many possible Class 0/I/II sources have been detected by the spitzer c2d survey using MIPS (Harvey et al. 2007b); and using both MIPS and IRAC (Harvey et al. 2007a). The region observed in this study is focused on the Serpens main cloud core, which contains the well known submillimetre Class 0-1 objects SMM1-11 (Casali et al. 1993; Davis et al. 1999), Hogerheijde et al. (1999) presented high resolution interferometric observations of some of these cores in a variety of molecular tracers. Evidence for infall towards SMM 2, 3 and 4 has been found (see e.g. Gregersen et al. 1997), further supporting the view that these are very young sources currently undergoing star formation. Duarte-Cabral et al. (2010) find evidence that the global structure of the cloud implies it consists of two colliding sub clouds.

1 http://www.jach.hawaii.edu/JCMT/surveys/gb/

Figure 1. The noise on the 13CO map: the root mean square integration of a line free region from a nearest-neighbour gridded map with 7.27 arcsecond pixels and 1 km s^-1 channels.

Much evidence of molecular outflows has been detected in the region in previous JCMT observations (White et al. 1995, Davis et al. 1999, Hodapp) (1999) measured the proper motions of H2 jets in the north-west part of this region (in the vicinity of SMM 5, 9 and 10), further connecting these jets to outflow sources. The observations were centred on the region known as the Serpens cloud core, containing many protostars, dust sources, HH objects and potential outflows. Eiroa et al. (2008) presented a recent review of the entire Serpens region. This paper presents new observations and results of outflow kinematics along with the general cloud properties.

2 OBSERVATIONS

Observations of the Serpens molecular cloud in the J = 3 → 2 CO rotational transition were obtained using HARP at the JCMT. 12CO observations were obtained in April and July 2007, while 13CO and C18O observations were obtained simultaneously in August 2007.

The telescope’s main beam efficiency 2ηMB is 0.63, taken from Buckle et al. (2009), where it was calculated from observations of planets. Each map was taken in ‘raster-scan’ mode. The telescope continually scans rows back and forth across the science region, writing out the data every 7.27 arcseconds. The telescope regularly observes a reference position to correct for the atmospheric distortion. In order to minimise the variation of the noise across the map half the observations scan along the longer axis of the rectangular area being observed, and half along the shorter axis. The JCMT beam size at 345.796GHz (12CO J = 3 → 2) is 14.6", at 330.88 GHz (13CO) it is 15.2", and at 329.331 GHz (C18O) it is 15.3".

In total 3.5 hours was spent observing the 12CO and 6 hours observing the 13CO & C18O. The observations were taken with a channel width of 0.42 km s^-1 for 12CO and 0.06 km s^-1 for 13CO and C18O. These were resampled onto 1 km s^-1 for the 12CO and 0.1 km s^-1 for the 13CO and C18O. The achieved noise levels on an un-smoothed, nearest neighbour gridded map were 0.10 K in 1 km s^-1 for 12CO and 0.93 and 0.88 K in 0.1 km s^-1 channels for C18O and 13CO respectively. The 12CO has significantly exceeded
the survey target rms level, which is 0.3 K in 1.0 km s$^{-1}$ channels. However, the $^{13}$CO and C$^{18}$O noise levels are significantly higher than the survey target rms (0.88 and 0.93 K compared with a target of 0.3 K in 0.1 km s$^{-1}$) therefore more observations are ongoing on this region, to reduce the co-added noise to the required level. This will allow more detailed follow up work on the core kinematics; however, the current noise level is more than adequate to study the bulk gas conditions and energetics across the entire region.

One of the requirements of the GBS is to achieve reasonable rms uniformity across the scans. As a multi-detector array, HARP naturally has some variation in system temperatures for each detector, and additionally during the Survey science verification phase (in which these data were taken) not all detectors in the 4x4 array could be used, therefore completely even noise was not achieved. We illustrate the uniformity of the noise achieved in Fig. 1, which shows the rms values across the $^{13}$CO map. As can be seen, the variation is low and although a grid pattern can be seen, it is constant across the map.

After the data were taken, the scans were analysed and for each scan the detectors showing anomalous baseline structure or excessive noise were removed from the reduction. The remaining data had a first order baseline fitted to line free regions of the spectra. This baseline was removed and the data were co-added, using nearest neighbour gridding. The rest of the images shown here and used for analysis are gridded onto 3 arcsecond pixels. The $^{12}$CO data from each detector were re-scaled to correct for striping caused by varying detector responses (see Curtis et al. 2010 for technique). A Gaussian kernel (using a FWHM of 9″) was used to grid these cleaned raw files into position-position-velocity cubes for each isotologue (giving an effective beam size on the maps of 17″). The C$^{18}$O and $^{13}$CO data files were gridded into separate files for each scan using a 10″ FWHM Gaussian kernel, then the resulting files were mosaiced together using an 8″ FWHM Gaussian kernel (giving an effective beam size for the maps of 20″). This larger effective beamsize was used in order to increase the signal to noise of the maps. In the $^{12}$CO reduced cube there was an anomalous baseline feature present in channels from 35.8 to 44.8 km s$^{-1}$. The shape was similar to other known instrumental effects in HARP/ACSIS data at the time the data were taken. The affected velocity region was blanked out, and then these channels were interpolated from surrounding data. Across most of the map there is no emission at these affected velocities, with only a small region containing the tail of a high velocity outflow having visible emission. The structure of the high velocity tail affected in these spectra appears to be well matched by the simple interpolation.

The resulting noise measurement for the Gaussian smoothed maps used in the scientific analysis is 0.017 K for the $^{12}$CO in 1 km s$^{-1}$ channels, and 0.19 K for both the $^{13}$CO and C$^{18}$O respectively, in 0.1 km s$^{-1}$ channels.

### 2.1 12CO map

The $J = 3 → 2$ transition of the CO isotopologues observed here have critical densities of the order of $10^{4–5}$ cm$^{-3}$. Tracing these high densities allow us to look at the dense gas more intimately involved with the ongoing star formation than lower transitions, tracing lower densities, allow. It also allows us to examine the higher temperature emission from molecular outflows, as these transitions occur at a correspondingly higher energy level – 31–33 K – than the lower transitions.

Fig. 2(a) shows the integrated $^{12}$CO emission; Fig. 5 overlays IR sources, submillimetre continuum sources and Herbig Haro (HH) objects. As is evident from the integrated emission alone, the region is a complex, clustered star-forming region. The ‘finger-like’ extensions so common to CO observations in many regions are clearly discernible; however, it should be noted that these do not always correspond to obvious spatially compact bipolar outflows.

Our $^{12}$CO $J = 3 → 2$ map covers a region of 260 square arcminutes centred on RA:18$^{h}$29$^{m}$45$^{s}$ Dec:+1$^{°}$35′57″ (J2000). The region was extended westwards to follow the strong bow-shock that culminates in the Herbig Haro object HH 106. This extended section has higher noise and was not followed up in $^{13}$CO and C$^{18}$O. The integrated intensity map in Fig. 3 is not dominated by emission at the systemic velocity of the cloud, presumably at least in part due to the strong self absorption present in the $^{12}$CO spectra. Fig. 4 presents the spectra for all three isotopologues plotted on the same axes for each of the SMM cores, and Fig. 5 shows spectra from some typical positions throughout the cloud. Many of the $^{12}$CO spectra exhibit either a double-peaked profile or a distorted Gaussian shape. By comparing the peak intensity and shape of the C$^{18}$O spectra from the same position as the $^{12}$CO, it is clear that the shapes of the $^{12}$CO line profiles appear to be caused by self absorption rather than multiple velocity components.

The $^{12}$CO emission is, therefore, dominated by the less dense blue and red-shifted high velocity gas of the cloud. The absorption maximum appears slightly red shifted with respect to the local rest velocity – perhaps indicative of global infall in the cloud, as one would expect in a star forming region. There are also prominent velocity wings present in the $^{12}$CO spectra as can be seen in Fig. 4, indicating the presence of molecular outflows in the region, some with velocities up to 20 km s$^{-1}$ with respect to the local rest velocity. These outflows have been observed before with molecular tracers (Olmi & Testi 2002; McMullin et al. 2000; Davis et al. 1999; White et al. 1995) and with masers (Moscadelli et al. 2005); however the data presented here improve on the resolution of the previous single dish CO studies. Recent Spitzer observations ( Harvey et al. 2007) have identified several deeply embedded sources within the Serpens molecular cloud – we would expect these sources to be of a Class 0 or early Class I nature and thus drive powerful molecular outflows. Fig. 6 shows the integrated $^{12}$CO emission, with the positions of YSO candidates, SCUBA cores and HH objects also displayed. We can see that the Spitzer deep sources align with the sources in the 850 μm SCUBA image, which are known in the literature as the 10 SMM sources, SMM 1-11, although note that there is no SMM 7. SMM 7 was first identified by White et al. (1995) at RA: 18$^{h}$29$^{m}$55.6$^{s}$ Dec:+01$^{°}$14′52″, but was not detected in the SCUBA map of Davis et al. (1999). There is not a clear C$^{18}$O emission peak present at its position in Fig. 2(d).

Fig. 6 shows the SCUBA 850 μm emission from Davis et al. (1999) with contours of red and blue shifted gas in $^{12}$CO demonstrating that there are a large number of molecular outflows associated with the Serpens sources. These maps are at a higher resolution than previous $^{12}$CO studies, allowing more accurate flow and source identification, compared to the previous results of Davis et al. (1999), where some of the flows are unresolved. Fig. 7 shows another view of the $^{12}$CO velocity structure of the cloud. In this three-colour image showing the red-shifted, blue-shifted and ambient emission (green) the strong red and blue lobes can be clearly seen.
2.2 \textsuperscript{13}CO and C\textsuperscript{18}O maps

The isotopologues \textsuperscript{13}CO and C\textsuperscript{18}O are much less abundant than \textsuperscript{12}CO, with the abundance ratio for the ‘local’ ISM being calculated as $X_{\text{\textsuperscript{13}CO}}/X_{\text{\textsuperscript{12}CO}} = 77$ (Wilson \& Rood 1994). Being less abundant, these species are only seen on the denser parts of the sub-clusters, allowing us to probe the motions of the gas more closely associated with the protostars rather than the outflowing gas. Our \textsuperscript{13}CO and C\textsuperscript{18}O maps (Fig. 2) cover a region of 17×11 arcminutes centred on RA 18\degr29\textquotesingle58\textquotesingle, Dec 1\textdgr13\textquotesingle02\textquoteright (J2000). Fig. 3 shows the SCUBA 850 \textmu m emission and overlays contours of the C\textsuperscript{18}O integrated intensity emission. We can see the C\textsuperscript{18}O emission traces the general shape of the dust and the filaments to the east and south identified by Davis et al. (1999) very clearly, although specific peaks do not align exactly with the position of the SCUBA cores. The C\textsuperscript{18}O spectra (in Fig. 4) show some evidence of multiple components.

\footnote{Measured in the Orion GMC}
GBS: First look at Serpens

components along the line of sight. This suggestion is strengthened by the analysis of Duarte-Cabral et al. (2010), who suggest that there are multiple velocity components and that the whole cloud can be modelled as two colliding flows or sub-clouds. These multiple velocity components from the C$^{18}$O emission should not be confused with the double-peaked structure of much of the $^{12}$CO emission. This occurs at very different velocity scales, hence our belief that it is due to self absorption of the line by nearer, cooler gas.

The correlation between the C$^{18}$O and the continuum emission suggests that the C$^{18}$O emission is not optically thick in the bulk of the emission. This is also consistent with the CO spectra shown in Fig. 4 where the $^{13}$CO still shows some self absorption from colder red shifted gas as seen in the $^{12}$CO spectra, whereas the C$^{18}$O spectra do not show such a clear pattern – although the presence of multiple components does make this less clear. In Sec. 3.1 we investigate the opacities of the isotopologues across the cloud.

It can be seen from these observations (see Fig. 2) that the $^{12}$CO and C$^{18}$O emission are tracing different gas structures – the C$^{18}$O emission looks very similar to the SCUBA emission, tracing a clumpy medium containing dense cores. The $^{12}$CO emission on the other hand is bright throughout the cloud, but is dominated by lobe-like filaments extending out from the cloud rather than clumpy emission in the centre of the cloud. The $^{12}$CO does not appear to be tracing the SMM cores. This suggests that the $^{12}$CO emission

\[\text{Integrated }^{12}\text{CO emission, with SCUBA cores (Di Francesco et al. 2008) shown as yellow squares, c2d Spitzer YSO candidates (Evans et al. 2009) shown as green triangles, and HH objects shown as red crosses (Davis et al. 1999). The 850\text\,\mu mSCUBA emission from Davis et al. (1999) is shown in contours.}\]

\[\text{Grey-scale image is the SCUBA 850\text\,\mu m emission from Davis et al. (1999). The blue contours represent blue shifted }^{12}\text{CO gas and red contours represent red shifted }^{12}\text{CO gas. The contour levels go up in 2.5 K km s}\text{^{-1}}\text{ steps, starting from 2.5 K km s}\text{^{-1}}\text{. The integration ranges are -4 to 4 km s}\text{^{-1}}\text{ for blue shifted gas and 14 to 22 km s}\text{^{-1}}\text{ for red shifted gas. The positions of known HH objects (from Davis et al. (1999)) are shown as circles, see Fig. 19 for labelling.}\]
The GBS Serpens Team

Figure 4. Spectra from the 10 SMM positions shown in Fig. 2. All three isotopologues are shown on the same axes. $^{12}$CO is the highest intensity spectra (black), and $^{18}$O is the weakest (blue). $^{13}$CO is shown in red. Probably becomes optically thick in the gas surrounding the cores, and does not see all the way to the central infrared dense cores.

In order to look further at the different structures traced by the three isotopologues, Fig. 5 shows position-velocity (PV) diagrams taken along a line of constant declination through the position of SMM 1 in all three isotopologues. In this Figure the PV diagrams of both $^{13}$CO and $^{12}$CO show evidence of self-absorption dips in the centre of the line, which are not seen in the $^{18}$O. The $^{12}$CO emission also clearly shows strong evidence for red- and blue-shifted emission in the line wings, which is not clearly seen in the $^{13}$CO and entirely absent in the $^{18}$O maps. Again, this emphasises that the isotopologues are truly tracing different environments, and specifically that the $^{18}$O emission is not influenced by the molecular outflows, at least at the sensitivities of these data.

Figure 5. Spectra from HH 106 ($^{12}$CO only) and 3 typical non-core positions in the cloud. These were located at: 18:29:58.4 +1:13:21 (top right), 18:30:05.4 +1:16:30 (bottom left) and 18:30:03.4 +1:10:51.0 (bottom right). Colours as for Fig. 4.

Figure 7. Red-green-blue image of integrated intensity structure in $^{12}$CO. Red: 11.8-57.8 km s$^{-1}$. Green: 4.8-10.8 km s$^{-1}$. Blue: -42.2-3.8 km s$^{-1}$.

3 CLOUD CONDITIONS

3.1 Optical Depth

The variation of optical depth across the cloud can be examined by looking at the ratio of intensities of the different isotopologues, $I_{^{13}CO}/I_{^{18}O}$ and $I_{^{12}CO}/I_{^{13}CO}$, across the entire region being studied. The relation between the line intensity ratio and the optical depth (e.g. Rohlfs & Wilson 2000) at a specific velocity is:

$$\frac{T_{^{12}CO}}{T_{^{13}CO}} = \frac{1 - \exp(-\tau_{^{12}})}{1 - \exp(-\tau_{^{13}})}$$

Where $T$ is the brightness temperature, and $\tau$ is the optical depth.

Ratio maps were created, displaying the ratio of the peak intensities of the isotopologues, thresholded at a five sigma peak value. For optically thin emission, the ratio of the intensities of two
cubes (see Fig. 4), there is visible self absorption in the $^{13}$CO and the $^{12}$CO which would tend to limit the validity of this approach by underestimating the ratio by a varying amount across the map. Therefore, we follow the method in Ladd et al. (1998) and examine the ratio of the integrated intensities instead. Although the self-absorption will still cause the integrated $^{13}$CO intensity to be underestimated, this should be a lower fractional error than would occur if the intensity ratio at the velocity of the peak was used. This remaining systematic under-estimation will however boost the C$^{18}$O optical depth, particularly in the central regions where the $^{13}$CO self absorption is strongest.

Fig. 10 shows the ratio map for the $^{13}$CO/C$^{18}$O integrated ratio.

We then use:

$$\frac{\int_{-\infty}^{\infty} T_{13}(v)dv}{\int_{-\infty}^{\infty} T_{18}(v)dv} = \frac{\int_{-\infty}^{\infty} 1 - \exp[-\tau_{13}(v)]dv}{\int_{-\infty}^{\infty} 1 - \exp[-\tau_{13}(v)/f]dv}$$

(2)

where $\tau_{13}(v) = \tau_{13} \exp[-v^2/2\sigma^2]$, and $\tau_{18}(v) = \tau_{13}(v)/f$, to calculate the optical depth by numerically minimising the following function:

$$\left| \frac{\int_{-\infty}^{\infty} 1 - \exp[-\tau_{13} \exp[-v^2/2\sigma^2]/f]dv}{\int_{-\infty}^{\infty} 1 - \exp[-\tau_{18} \exp[-v^2/2\sigma^2]]dv} - \frac{\int_{-\infty}^{\infty} T_{13}(v)dv}{\int_{-\infty}^{\infty} T_{18}(v)dv} \right|$$

(3)

This method is very stable to the value of $\sigma$ that is chosen, therefore we have simply used an average line-width instead of estimating the Gaussian line-width for each spectra. We used $\sigma$ value corresponding to a line-width of 1.5 km s$^{-1}$, the FWHM of an averaged C$^{18}$O spectra. The abundance ratio can be calculated for optically thin lines by looking at the intensity ratio towards the edge of the cloud. We see values approaching the canonical value of 8 (Pierking et al. 1982), therefore we feel confident both in using this as the abundance ratio for $^{13}$CO/C$^{18}$O and that the C$^{18}$O emission really is optically thin across the cloud.

Across the map the $^{13}$CO/C$^{18}$O ratio varies from around 3-8 across the central region to values from 2.6-7.0 towards the cores, with most clustered around a value of 3. This gives $\tau_{18}$ values of 0.07 to 0.9 towards the cores, and $\tau_{13}$ values of 0.61 to 7.3. This suggests that the C$^{18}$O 3–2 emission is optically thin across the
map, and is even (marginally) optically thin towards the position of the submillimetre cores, and that the $^{13}$CO 3–2 emission is transitional between optically thick and thin across much of the cloud, and optically thick towards the dense cores. Fig. 11 shows the $^{12}$CO optical depth calculated across the map. It is very noticeable that the regions of high optical depth do not correspond to the positions of the submillimetre SMM cores. This is not unexpected, as the peaks of the $^{13}$CO emission do not align exactly with that of the continuum cores. However, the effect of the $^{13}$CO ceasing to be optically thin towards extremely dense regions, as well as the possibility of depletion towards the centre of dense cores and the slight self absorption present in the $^{13}$CO emission prevent us from investigating this further.

3.2 Excitation Temperature

The excitation temperature of the molecular gas can be calculated from the peak temperature of emission from optically thick gas (via the assumption of local thermodynamic equilibrium). In our observations however, the most optically thick tracer – $^{12}$CO – is complicated by the strong self absorption features seen in the $^{12}$CO line profiles across much of the cloud. This would underestimate the excitation temperature in these dense regions. However, as we have calculated that the $^{12}$CO emission is just optically thick across much of the cloud, we can also calculate the excitation temperature from this emission, using:

$$T_B = \frac{1}{\tau_B} = \frac{1}{\tau} - \frac{1}{\alpha}$$  \hspace{1cm} (4)

where $T_B$, the main beam temperature, is assumed to be the same as the peak temperature of the transition. $T_0$ is $h\nu/k_B = 16.6$ K for $^{12}$CO and $15.9$ K for $^{13}$CO, and $T_B$ is $2.73$ K is the temperature of the cosmic background. $\tau$ is the optical depth for the transition of interest and is assumed to be infinity here. This equation assumes that the emission completely fills the beam. This gives:

$$T_{ex}^{(12)CO} = \frac{16.6K}{\ln(\tau_{peak} + 1)}$$  \hspace{1cm} (5)

$$T_{ex}^{(13)CO} = \frac{15.9K}{\ln(\tau_{peak} + 1)}$$  \hspace{1cm} (6)

The results for both $^{13}$CO and $^{12}$CO are shown in Figs. 12 & 13. $^{12}$CO gives us a mean excitation temperature of $17$ K across the map, and temperatures towards the positions of the cores of 21-33 K. These positions will, however, be looking at the excited gas from molecular outflows instead of the cores themselves. These temperatures may be underestimated as the $^{12}$CO emission is strongly self absorbed towards the bulk of the cloud. However, by contrast the excitation temperature calculated from the $^{13}$CO emission is significantly lower—a mean temperature across the cloud of $13$ K, and temperatures towards the cores ranging from 16-22 K. This $^{13}$CO temperatures have been calculated assuming high optical depth. Although we have calculated the $^{13}$CO opacities towards the centre of the map (where they are highest), we do not have $^{13}$CO opacities for those regions towards the edges of the map where the $^{13}$CO emission is weak or not detected. Therefore we have not been able to correct for the $^{13}$CO opacity in these regions, but we expect that the assumption of high optically depth will be least valid in these areas. Caution must used when drawing conclusions from the excitation temperatures in these regions. The difference in temperatures derived from the $^{13}$CO and $^{12}$CO maps is interesting, particularly given that we expect the $^{12}$CO temperature to be significantly underestimated due to the stronger self absorption. Fig. 14 suggests that the excitation temperature estimated from the $^{12}$CO appears to trace some of the outflow structure in this cloud. This can be most clearly seen in the hot lobe-like structure visible in the NW of Fig. 13. This structure corresponds to the position of HH 460, and there is known bright H$_2$ emission in the region. This suggests that shocks are primarily responsible for producing the higher $^{13}$CO temperatures.
Table 1. Summary of the energetics of the Serpens Molecular cloud

| Energy (M⊙ km² s⁻²) |
|---------------------|
| Gravitational Binding 245 |
| Turbulent kinetic 220 |
| Global Outflow Kinetic Energy -along line of sight 51 |
| -assuming random inclination 153 |

Global Energetics

We can compare the different energetics present in the cloud by making some simple approximations. We can estimate the gravitational binding energy and the turbulent kinetic energy using the following equations:

\[
E_{\text{grav}} = \frac{3GM^2}{5R} \tag{9}
\]

\[
E_{\text{km}} = \frac{3}{2}M\sigma^2 \tag{10}
\]

where \( G \) is the gravitational constant, \( M \) is the mass of the gas in the cloud, \( R \) is the estimated size of the cloud, and \( \sigma \) is the estimated 1-D velocity dispersion in the cloud, equal to \( v_{\text{fwhm}}/2.35 \). This assumes a uniform density cloud. A more centrally condensed cloud would be more tightly bound (i.e. would have a more negative gravitational binding energy). Similarly, due to the \( M^2 \) factor involved, the uncertainties in the mass of the cloud will produce a large uncertainty in the gravitational binding energy. The error in the assumption of a single velocity dispersion for the entire cloud will also produce large uncertainties in these values, due to the \( \sigma^2 \) factor.

The virial mass calculated above corresponds to a gravitational binding energy of 245 M⊙ km² s⁻². The turbulent kinetic energy can be estimated by measuring the CO line width in regions where the emission is not affected by outflow activity, therefore we use the optically thin tracers. The \(^{13}\)CO and \(^{18}\)O maps give roughly similar results of \( \sim 1.5-2 \) km s⁻¹ for the line width. 2 km s⁻¹ is used here, giving a turbulent kinetic energy of 220 M⊙ km² s⁻².

The energetics of the cloud are summarised in Table 1 along with the global outflow energy from Sec. 3.4.

This analysis suggests that the cloud is gravitationally bound. However, it is important to reiterate that there are large uncertainties in the estimates of the values presented here.

We can also examine the importance of the outflows in this region. The outflow momenta and energy have been derived by assuming that the measured CO line width is the result of random inclination 153 -along line of sight 51 -assuming random inclination 153.

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3.4 Global Energetics

We can compare the different energetics present in the cloud by making some simple approximations. We can estimate the gravitational binding energy and the turbulent kinetic energy using the following equations:

\[
E_{\text{grav}} = \frac{3GM^2}{5R} \tag{9}
\]

\[
E_{\text{km}} = \frac{3}{2}M\sigma^2 \tag{10}
\]

where \( G \) is the gravitational constant, \( M \) is the mass of the gas in the cloud, \( R \) is the estimated size of the cloud, and \( \sigma \) is the estimated 1-D velocity dispersion in the cloud, equal to \( v_{\text{fwhm}}/2.35 \). This assumes a uniform density cloud. A more centrally condensed cloud would be more tightly bound (i.e. would have a more negative gravitational binding energy). Similarly, due to the \( M^2 \) factor involved, the uncertainties in the mass of the cloud will produce a large uncertainty in the gravitational binding energy. The error in the assumption of a single velocity dispersion for the entire cloud will also produce large uncertainties in these values, due to the \( \sigma^2 \) factor.

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This virial mass is approximately 80 percent of the measured \(^{13}\)CO mass, suggesting that the cloud is in a bound state. However, this result is of course subject to the same sort of systematic uncertainties as the mass estimate.. These large uncertainties prevent us from drawing a more firm or quantitative conclusion about the state of the cloud other than to estimate that the measured \(^{13}\)CO mass is close the virial mass, even if we attempted to use a more complex model of the density.
in the estimation of these variables (as mentioned in the discussion of the mass, and in further discussion in Sec. 5.1). Further work on disentangling the individual outflows and on analysing the detailed structure of the entire region will be required to quantify this more accurately, possibly using observations of other tracers.

4 VELOCITY STRUCTURE FROM C$^{18}$O

The C$^{18}$O emission, which is not tracing outflows and is optically thin across the whole extent of the Serpens cloud, allows us to study the velocity structure of the cloud in detail, with no obvious contamination from infall and outflow motions at the sensitivity of these observations. In the following sections we will analyse the velocity structure using velocity-coded 3-colour plots and position-velocity diagrams through the region, to try to understand the general dynamics of the region.

4.1 Global velocity

The velocity structure of the dense gas of the Serpens cloud can be seen on Fig. 14 as a velocity coded 3 colour plot. A first glance at this figure shows that the blue shifted emission is east of the Serpens filament, whereas the red emission is mainly west of it. This gradient has been previously detected by other authors (Olmi & Testi 2002), who interpreted it as a global rotation of the cloud. However, this conclusion was limited by the resolution of their data, which could not resolve the velocity structure in as much detail as we can.

Figure 14 demonstrates that this velocity structure is more complex than simple rotation, by showing a 3 colour plot of the C$^{18}$O red-shifted, blue-shifted and central-velocity emission. For instance, we can see, in the SE end of the Serpens filament (the SE sub-cluster) a sharp merger/overlap of the blue and the red emission, not expected in a solid body rotation scenario. On the other hand, the NW end of the filament (the NW sub-cluster) has very little blue-shifted emission. This velocity structure was also suggested to be possibly a shear motion (Olmi & Testi 2002) or a collision of two clouds/flows where the interface coincides with the SE end of the filament (Duarte-Cabral et al. 2010).

Another noticeable feature visible in this view of the C$^{18}$O velocity structure, are the gas streams east of the filament. Note that these are not seen at the west, nor do they correlate with any of the outflows seen in $^{13}$CO. These small filaments roughly perpendicular to the main filament are commonly seen in filamentary molecular clouds, but their origin is not yet clear (Myers 2009).

4.2 Position-Velocity Diagrams

In order to look at the velocity structure at specific positions we have created PV diagrams. By studying several PV diagrams from our C$^{18}$O maps, we can get a better sense of how the velocity changes and evolves across the cloud. Our approach to such a study involves several cuts both with constant Declination and with constant RA. Fig. 15 shows the positions of the PV cuts used here.

Figs. 14 and 17 shows PV diagrams (horizontal slices of the data cube) at five fixed Declinations, varying the Right Ascension. Fig. 16 cuts through the NW sub-cluster, where we can note that this sub-cluster is represented by a velocity mainly between 8 and 8.5 kms$^{-1}$. However, there is some lower velocity gas weakly emitting east of the sub-cluster, with velocities around 7.5 kms$^{-1}$. Whether this gas is physically connected with the higher velocity gas is not clear, as it could either represent a separate cloud with a slightly different velocity, or the same cloud undergoing rotation. Therefore, we must examine the the evolution of these components as we look southwards through the cloud in order to understand what these gas components are tracing.

Fig. 17 shows the velocity structure of the SE sub-cluster. Here the two velocity components, which in the north are very well separated, begin to merge. As we move south the components become more offset from each other in velocity, and we see regions that are clearly reproduced by two velocities (one around 7 kms$^{-1}$ and the other around 8.5 kms$^{-1}$). Note that the regions which also show dust emission are coincident with regions where the two velocities coexist along the line of sight. Finally, the lower velocity gas ceases to exist, and at the very southern end of the filament

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Figure 14. Velocity coded 3 colour plot of the C$^{18}$O $J = 3 \rightarrow 2$ Each colour represents the maximum value in the following velocity intervals: blue: 5 - 7.7 kms$^{-1}$; green: 7.7 8.3 kms$^{-1}$; and red: 8.3 11 kms$^{-1}$

Figure 15. Integrated C$^{18}$O map showing the positions of the PV diagrams used in this section.
solely consists of the higher velocity gas, at around 8.3 km s$^{-1}$.

We also study the velocity structure using vertical PV diagrams (constant RA) in Fig. 18. The information we get from here adds to the horizontal diagrams, in the sense that we can confirm the complex velocity structure, including the double velocity component towards the south sub-cluster (best seen on Fig. 18 top right panel). We can also see velocities below 8 km s$^{-1}$ towards the northern region, in the first two panels. Because this corresponds to higher RA positions, these lower velocities in the north are only seen in regions offset to east from the sub-cluster seen in 850 µm emission. The two last panels of Fig. 18 (bottom row, centre and right panels) show the bulk of emission towards the NW sub-cluster, which traces well the 850 µm continuum emission, showing us the velocities all concentrated between 8 and 8.5 km s$^{-1}$, the outflow structure of the cloud is complex. Although there appear to be many outflows in this region, many are overlapping. Instead of attempting to assign spectra arbitrarily to one or another of an overlapping outflow in order to calculate their properties, we have decided to look first at the global outflow properties (i.e. energetics for the all the high velocity gas), and then to look individually at those outflows that can be spatially located via their very high velocity emission.

5 OUTFLOWS

5.1 Global Outflow Properties

To calculate the global outflow properties, we wish to look at all the gas that is moving at a significantly red- or blue-shifted velocity from the line centre. However, it is not possible to completely exclude the ambient emission, and some proportion of this will also be included in these calculations.

We can calculate some basic kinematic properties for the global properties of the outflowing gas. Examination of the spectra in the cloud shows that ambient $^{12}$CO spectra away from the outflows appear to cover a velocity range of 6 to 10 km s$^{-1}$. This is assumed to include ambient emission for the entire cloud and is excluded from the integration. Therefore the integration ranges used are -15 to 6 km s$^{-1}$ for the blue-shifted emission and 10 to 30 km s$^{-1}$ for the red-shifted emission.

The masses were calculated under the assumption of LTE, a distance of 230 pc and assuming optically thin emission in the line wings with an excitation temperature of 50 K (Davis et al. 1999, White et al. 1995). Although this is higher than the peak excitation value we calculated earlier, it is expected that the gas in the outflows will be considerably warmer than that in the bulk of the gas.
Figure 16. Horizontal position-velocity diagrams in grey scale and contours of the $^{18}$O $J = 3 \rightarrow 2$ emission. These represent the typical velocity structure in the NW sub-cluster. The diagrams are displayed with decreasing Declination, i.e. from North to South, and at constant Declinations of $1^\circ 16' 24"$ (top) and $1^\circ 15' 24"$ (bottom). Right Ascension varies from $18^h 30^m 18.5^s$ to $18^h 30^m 18.5^s$ (offset of 277 to -412 respectively) on both diagrams. The dust emission seen in 850 $\mu$m lies between the dotted lines.

Figure 17. Horizontal position-velocity diagrams in grey scale and contours of the $^{18}$O $J = 3 \rightarrow 2$ emission. These represent the typical velocity structure in SE sub-clusters. The diagrams are at constant Declination (from top to bottom panel) of $1^\circ 13' 24", 1^\circ 12' 24", 1^\circ 10' 24"$ and $1^\circ 08' 24"$. Right Ascension varies from $18^h 30^m 18.5^s$ to $18^h 30^m 18.5^s$ (offset of +277" to -412" respectively) on all the diagrams. The dust filament seen in 850 $\mu$m lies between RA offsets of -120" and -180".

$$M_{\text{CO}} = 2.2 \times 10^{-6} \left( \frac{X_{\text{CO}}}{10^{-13}} \right)^{-1} \left( \frac{\mu}{1.085} \right)^{-1} \left( \frac{K}{A_{\text{mm}} \text{square} \text{arcsecond}} \right) \int T_A^* (v) dv M_\odot$$

(11)

The momentum and energy are estimated similarly, by replacing $\int T_A^* dv$ by $\int T_A^* (v - v_0) dv$ and $0.5 \times \int T_A^* (v - v_0)^2 dv$, where $v_0$ is the central velocity. Here, an average central velocity value is used for the whole cloud.

The global results for the Serpens cloud are summarised in Table 2. In Table 2 we give the total energy from both global outflow values; 50 $M_\odot$ km$^2$ s$^{-2}$. It is of course again important to consider the sources of systematic uncertainty affecting these figures. Our assumption of the excitation temperature of 50 K, our chosen value for the CO abundance, and our assumption of LTE are sources of uncertainty in these values. We also expect some proportion of the shocked gas to be disassociated from its molecular form, and this will be a larger effect at the high velocities. We have also assumed that the entire line wing is optically thin; in fact this may well not be true, especially at the velocities close to the ambient cloud emission. This effect may mean that our values for the outflow masses are significantly underestimated. There may also be an effect on the momentum and energy estimated, but the optical depth is likely to be a less important factor and the disassociation a larger factor as these values are dominated by the high-velocity emission. These effects would tend to increase the values shown here. It is also important to reiterate that there will be some contamination of the values shown here by the ambient gas.

Eqn. (11) only provides us with the energy and momentum along the line-of-sight, and we must correct for the inclination of the outflows if we wish to calculate 3-D values. The outflow velocity should be corrected by $1/\cos(i)$ from the line-of-sight velocity, where $i$ is the inclination angle. If we assume that the outflows are in an isotropic random distribution, this will increase the momentum by a factor of 2 and the kinetic energy by 3.

We have also made a rough estimate of the dynamical age of the outflows in the region. An estimate of the average flow lobe length was found from Fig. 6 of 210 arcseconds (0.23 pc at $D = 230$ pc) in the plane of the sky. The average maximum velocity in the line of sight is $\sim 14$ km s$^{-1}$, thus obtaining a value of
Table 2. Global outflow properties, both along the line-of-sight only (l.o.s.) and corrected for a random distribution of inclinations (corr.).

|       | Mass/$M_\odot$ | Momentum/$M_\odot$ km s$^{-1}$ | Energy/$M_\odot$ km$^2$ s$^{-2}$ |
|-------|----------------|---------------------------------|----------------------------------|
|       | Blue           | 1.3                             | 6.1                              | 28                               |
|       | Red            | 1.8                             | 6.3                              | 23                               |
| corr. | Blue           | -                               | 12.2                             | 84                               |
|       | Red            | -                               | 12.6                             | 69                               |

1.6×10$^4$ yr. This very young age agrees with the conclusions in the literature that the Serpens sources are Class 0/I YSOs (Casali et al. 1993; Testi & Sargent 1998). The values for these energetic properties correspond well to those found in Davis et al. (1999).

5.2 Effect of outflows on global energetics

The results in Tables 1 and 2 allow us to discuss the validity of the theory of supersonic turbulence sustained by molecular outflows.

If we apply a correction for random inclination, we estimate the total kinetic energy contained in the outflows to be of order 70 per cent of the total turbulent kinetic energy (see sec. 3.2). This suggests that the outflows are a strong influence on the structure and energetics of the Serpens cloud core, and studies of this region must take care to account for them (particularly with respect to small scale structure).

Our finding that the turbulent kinetic energy and the global outflow energy are of comparable size fits well with theories and simulations that involve the driving of supersonic turbulence by outflows in regions of active star formation (see e.g. Li & Nakamura 2006; Matzner 2007). However, it is still necessary to identify a mechanism that can convert the outflow momentum (directed outwards from the cloud) into the turbulent energy. An analytical model for this process was developed by Matzner (2007), who proposed that molecular cloud turbulence can be driven by collimated protostellar outflows, resulting in a cascade of momentum rather than energy. Numerical simulations by Li & Nakamura (2006) and Carroll et al. (2009) appear to be consistent with this picture.

A further interesting comparison can be made between the turbulent kinetic energy and the gravitational binding energy. Since the binding energy is very similar to the turbulent kinetic energy, this suggests that the entire cloud is only weakly bound and that some small, local, regions may well be in a state of collapse where as others are in a state of expansion. This is one of the expected outcomes of the theory of star formation control by supersonic turbulence (see McKee & Ostriker 2007 and references therein, e.g. Mac Low & Klessen 2004). Further insight can be gained by considering the ratio of kinetic outflow energy to gravitational binding energy. A value of ~ 0.7 is indicative that outflows are extremely important to understanding the cloud support mechanism. However, we expect the uncertainties in the estimation of the various parameters are large enough to prevent a more firm conclusion.

5.3 Individual Outflows

As can be seen from the $^{12}$CO channel maps presented in Fig. 19, the $^{12}$CO high velocity structure is extremely complex – identifying outflows from the $^{12}$CO emission alone is extremely difficult.

We see considerable ‘finger-like’ structures in this region, that correspond to large scale outflow structure across the cloud. Although areas containing high velocity red- and blue-shifted gas can be seen clearly in the channel maps, categorising these into neat bipolar lobes is not so simple. However, there are reasonable amounts of complementary data available. The presence of known HH objects are indicated on Fig. 9 and a comparison with the positions of known cores allows a few more clear-cut outflows to be identified. Figs. 22 and 23 show PV diagrams along some of these outflows.
blue lobe. It has a minimum velocity of 9 km s$^{-1}$, with the fastest part of the feature being present at the farthest spatial distance from the main cloud. It does not clearly trace back to any source within the cloud. There is some red-shifted emission slightly north and west of this feature, but this appears to connect back further within the cloud.

D: Towards the position of HH 460 we see the end of a strong blue-shifted lobe. There is also some much weaker red-shifted emission. The maximum blue-shifted velocity in this region is at around -11 km s$^{-1}$.

5.3.2 Extremely high velocity emission

In order to attempt to separate some of this confused outflow structure in this region, we can look at those outflows that have emission at very high velocities – of order 10 km s$^{-1}$ away from the line centre. Fig. 21 shows contours of intensity maps of the $^{12}$CO data integrated from 24-34 km s$^{-1}$ and from -15 to -5 km s$^{-1}$. These are overlaid on the C$^{18}$O integrated intensity map. By only looking at the outflows with this extreme velocity range, we are missing out much of the outflowing material in the cloud. However, this reduces the complexity of the velocity structure, and allows us to be fairly confident that we are not including a large amount of ambient emission. This method also allows us to spatially separate otherwise confused and overlapping outflows, and thus calculate properties of specific outflows.

As can be seen in Fig. 21, several regions seem to show compact features around cores, suggesting the presence of outflowing material.

A: Specifically around SMM 6, 3 and 4, in the centre of the map, what appears to be at least two overlapping outflows can be seen.
The blue shifted contours show two peaks, one at SMM4 and one around SMM6 and 3. HH 458 is also centred on this region.

B: SMM 1 and 9 also both show overlapping red and blue lobes, which again appear to belong to two separate outflows. Here the emission from SMM 1 appears to be much larger than that around SMM 9.

C: There is a strong region of compact red-shifted emission to the north of SMM 8, however visual inspection of the $^{12}$CO data cube does not reveal any adjacent very-high-velocity blue-shifted emission that can be separated from the main line centre emission. The red shifted emission is however also near HH 459 so may be connected with that. In the absence of any blue-shifted emission it is not possible to identify this feature as indicating a molecular outflow, therefore we have identified this as tentatively connected with the HH object 459, but have not attempted to link it directly to a submillimetre source.

D: South-east of SMM 11 there is some evidence of adjacent red and blue compact regions of emission (in Fig. 21 the blue contoured region is more clearly seen). Inspection of the data cube suggests that the red and blue structure exists more clearly at less extreme velocities. However, given the lack of an obvious source it is not clear whether or not this represent a bipolar outflow. Additionally, inspection of spectra in the red shifted region suggests it is possible that the high velocity red-shifted component may be due to an additional velocity component along the line of sight instead of excess line wing emission, so the spatial connection of the red and blue emission may be coincidental. It has not been possible to associate this red/blue region with a submillimetre source.

For the outflows in the SMM 3, 4 and 6 region and in the SMM 1 and 8 region we have calculated their properties. As these appear to slightly overlap spatially, it was not possible to perfectly separate these into the four separate outflows we believe exist. Instead, a simple best guess has been taken (on the basis of the contours of the extremely high velocity gas), and spatial regions that appear to contain most of the outflow emission. These spatial regions have then been used to calculate red and blue shifted mass, momentum and kinetic energy for each outflow, using the same assumptions as for the global outflow properties. No attempt has been made to correct for the angle of inclination.

The velocity ranges used in the calculations were -30 to 1.8 km s$^{-1}$ and 17.8 to 36.8 km s$^{-1}$. The spatial regions were defined separately for the red- and blue-shifted emission for each outflow. The masses calculated are shown in Table 3. Again, no attempt was made to correct for inclination.

The total mass for these outflows comes to merely 0.03 $M_{\odot}$ for the blue-shifted emission and 0.01 $M_{\odot}$ for the red-shifted emission; this seems low considering the global values we have previously calculated. However, we have been very conservative with the velocity range used here, attempting to be sure that we are not being contaminated by the line centre emission or by overlapping outflows that do not reach such high velocities. If we use the same velocity ranges as used for the global properties than these values approximately double, making these outflows responsible for most of the high velocity mass in this cloud.

To further show that these outflows are indeed connected with the cores, Fig. 22 shows position-velocity diagrams along the outflows identified. Evidence of the outflow emission can be seen in both the red and blue shifted regions, although it is the central line emission that dominates. The dip in the centre of the line shows the self absorption in the $^{12}$CO emission.

| Table 3. Outflow masses and line of sight energetics for $^{12}$CO emission in range -30 to 1.8 km s$^{-1}$ (blue) and 17.8 to 36.8 km s$^{-1}$ (red) for each outflow. Note that these outflows are spatially defined on the basis of their extreme velocity emission – closer to the ambient velocity they are spatially substantially larger (and more confused), and the values presented here are very much lower limits for these specific outflows |
|---|---|---|---|
| Mass (M$_{\odot}$) | SMM 4 | SMM 6 & 3 | SMM 1 | SMM 8 |
| Red | 0.0016 | 0.0085 | 0.012 | 0.003 |
| Blue | 0.0021 | 0.0016 | 0.0052 | 0.0015 |
| Mom (M$_{\odot}$ km s$^{-1}$) | SMM 4 | SMM 6 & 3 | SMM 1 | SMM 8 |
| Red | 0.0014 | 0.0012 | 0.0043 | 0.0010 |
| Blue | 0.0018 | 0.0028 | 0.0042 | 0.00084 |
| Energy (M$_{\odot}$ km$^2$s$^{-2}$) | SMM 4 | SMM 6 & 3 | SMM 1 | SMM 8 |
| Red | 0.0095 | 0.0097 | 0.040 | 0.0080 |
| Blue | 0.012 | 0.0021 | 0.034 | 0.0058 |

6 SUMMARY

High resolution mapping of the Serpens molecular cloud in the $J = 3 - 2$ transition of $^{12}$CO, $^{13}$CO and C$^{18}$O was performed with HARPS at the JCMT. The $^{12}$CO map traces the numerous outflows in the region, with line wings detected out to ~30 and +37 km s$^{-1}$. The C$^{18}$O map was used to examine the global velocity structure and to estimate the mass of the region, which was found to be ~205 $M_{\odot}$. Intensity ratios were also used to estimate an abundance ratio for $^{13}$CO to C$^{18}$O and in turn an estimate of the optical depth. Additionally, the kinetic temperature was examined.
The global velocity structure of Serpens was examined in the C$^{18}$O emission, and evidence was found to support the conclusion of Duarte-Cabral et al. (2010) that the cloud consists of two sub clouds at different velocities.

Although across the bulk of the cloud it would not be straightforward to identify the individual outflows present as they overlap spatially, the global properties of the outflowing gas were examined, and we found that the total outflow energy (corrected for random inclination distribution) was approximately 70 percent of the total turbulent energy in the region. This suggests that the outflows may be a significant factor in driving turbulence in this star-forming region, in broad agreement with many recent simulations and theory.

Four compact outflows towards five of the submillimetre sources were identified on the basis of extremely high velocity emission and their properties examined, finding that this extreme gas does not contribute a large portion of the global outflow energy.

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