CARMA CO($J = 2 − 1$) OBSERVATIONS OF THE CIRCUMSTELLAR ENVELOPE OF BETELGEUSE

EAMON O’GORMAN1, GRAHAM M. HARPER1, JOANNA M. BROWN2, ALEXANDER BROWN3, SETH REDFIELD4, MATTHEW J. RICHTER5, AND MIGUEL A. REQUENA-TORRES6

1 School of Physics, Trinity College Dublin, Dublin 2, Ireland
2 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS-78, Cambridge, MA 02138, USA
3 Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309-0389, USA
4 Astronomy Department, Van Vleck Observatory, Wesleyan University, Middletown, CT 06459, USA
5 Physics Department, UC Davis, 1 Shields Avenue, Davis, CA 95616, USA
6 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

Received 2012 February 10; accepted 2012 May 25; published 2012 June 26

ABSTRACT

We report radio interferometric observations of the $^{12}$C$^{16}$O $J = 2 − 1$ emission line in the circumstellar envelope of the M supergiant α Ori and have detected and separated both the S1 and S2 flow components for the first time. Observations were made with the Combined Array for Research in Millimeter-wave Astronomy (CARMA) interferometer in the C, D, and E antenna configurations. We obtain good $u − v$ coverage (5–280 kλ) by combining data from all three configurations allowing us to trace spatial scales as small as 0′′9 over a 32′′ field of view. The high spectral and spatial resolution C configuration line profile shows that the inner S1 flow has slightly asymmetric outflow velocities ranging from $−9.0$ km s$^{-1}$ to $+10.6$ km s$^{-1}$ with respect to the stellar rest frame. We find little evidence for the outer S2 flow in this configuration because the majority of this emission has been spatially filtered (resolved out) by the array. We also report a SOFIA–GREAT CO($J = 12 − 11$) emission line profile, which we associate with this inner higher excitation S1 flow. The outer S2 flow appears in the D and E configuration maps and its outflow velocity is found to be in good agreement with high-resolution optical spectroscopy of K i obtained at the McDonald Observatory. We image both S1 and S2 in the multi-configuration maps and see a gradual change in the angular size of the emission in the high absolute velocity maps. We assign an outer radius of 4″ to S1 and propose that S2 extends beyond CARMA’s field of view (32″ at 1.3 mm) out to a radius of 17″, which is larger than recent single-dish observations have indicated. When azimuthally averaged, the intensity falloff for both flows is found to be proportional to $R^{-1}$, where $R$ is the projected radius, indicating optically thin winds with $\rho \propto R^{-2}$.

Key words: circumstellar matter – radio lines: stars – stars: individual (alpha Ori) – stars: late-type – stars: massive – supergiants

Online-only material: color figures

1. INTRODUCTION

The circumstellar envelope (CSE) of the M2 Iab supergiant Betelgeuse (α Orionis) is a proving ground for ideas and theories of mass loss from oxygen-rich M supergiants. Currently, it is losing mass at a respectable rate $\sim 3 \times 10^{-6} M_\odot$ yr$^{-1}$ (Glassgold & Huggins 1986; Huggins et al. 1994; Harper et al. 2001), as it has been over the past $\sim 1000$ yr. Most of the optically thin silicate dust lies beyond $\sim 46$ stellar radii (Danchi et al. 1994) and dust is, therefore, unlikely to be responsible for the bulk mass loss. This raises the important point that if the mass loss from Betelgeuse is not a result of dust then perhaps the same mass loss. This raises the important point that if the mass loss from Betelgeuse is not a result of dust then perhaps the same mass-loss mechanism and so spatial and dynamical studies of molecules are a fruitful line of investigation, especially in relation to eventual formation of dust. Such studies also allow us to calculate the timescales on which certain mass-loss episodes have occurred, and these can then be compared to the timescales of potential mass-loss initiators such as convection or magnetic dynamo cycles.

The study of CO molecules in the CSE of Betelgeuse began with the detection of 4.6 μm ro-vibrational absorption lines of $^{12}$C$^{16}$O and $^{13}$C$^{16}$O by Bernat et al. (1979) who identified two absorption features, implying two distinct structures within the overall outflow. One component, known as S1, has a Doppler shift of 9 km s$^{-1}$ toward us with $T_{\text{exc}} \simeq 200$ K, $v_{\text{turb}} \simeq 4$ km s$^{-1}$, and $N_{^{12}\text{C}^{16}\text{O}} = 4.7 \times 10^{17}$ cm$^{-2}$. The second faster component, known as S2, has a Doppler shift of 16 km s$^{-1}$ toward us with $T_{\text{exc}} \simeq 70$ K, $v_{\text{turb}} \simeq 1$ km s$^{-1}$, and $N_{^{12}\text{C}^{16}\text{O}} = 1.2 \times 10^{16}$ cm$^{-2}$. The S1 feature with its higher column density was well known from atomic absorption line studies (e.g., Weymann 1962) and both features had been detected in high spectral resolution atomic Na and K absorption profiles (Goldberg et al. 1975). $^{13}$C$^{16}$O was subsequently detected at 230 GHz in the $J = 2 − 1$ rotational emission line by Knapp et al. (1980), although a search for SiO($J = 2 − 1$) by Lambert & Vanden Bout (1978) had been unsuccessful. The weaker $^{12}$C$^{16}$O($J = 1 − 0$) line was tentatively detected by Knapp & Morris (1985) with a 7 m dish that had a half-power beamwidth (HPBW) of 100″.

Huggins (1987) presented a higher signal-to-noise $^{12}$C$^{16}$O ($J = 2 − 1$) observation of Betelgeuse’s CSE with an HPBW of 32$''$ and found some evidence for an S2 radius of about 16$''$ by comparing the $(2 − 1)/(1 − 0)$ intensities. However, a 30 m Institut de Radioastronomie Millimétrique (IRAM) $J = 2 − 1$ line profile was later presented by Huggins et al. (1994) and looked remarkably similar, even though it was observed with a smaller 12$''$ HPBW. The profile did not show the horned wing signature expected if it had been resolved apparently in conflict with the previous S2 radius estimate.

Here we present the results of an interferometric study of the rotational $^{12}$C$^{16}$O($J = 2 − 1$) emission line made using three Combined Array for Research in Millimeter-wave Astronomy (CARMA) configurations with HPBWs of 0$''$.9 (C), 2$'$.1 (D), and 4$'$.4 (E) designed to explore the S1 and S2 flows at these spatial scales. Preliminary results of the D configuration observations have been presented in Harper et al. (2009) as part of a multi-wavelength study of CO surrounding α Ori. We also present a supporting SOFIA CO($J = 12 − 11$) line profile in addition to high spectral resolution observations of the K$'$ 7699 A line. In Section 2 the observations and data reduction techniques are discussed and in Section 3 the results of the spectra and image maps are presented. Discussions and conclusions are presented in Sections 4 and 5, respectively.

2. OBSERVATIONS AND DATA REDUCTION

The millimeter observations were made with the 15 element CARMA interferometer (Scott et al. 2004), which is located at Cedar Flat in eastern California at an elevation of 2200 m. The array consists of nine 6.1 m antennas and six 10.4 m antennas formerly from the Berkeley Illinois Maryland Association (BIMA) and the Owens Valley Radio Observatory (OVRO) arrays, respectively. Table 1 summarizes the various observations which span the period 2007 May–2009 November. The observations were carried out in the C, D, and E configurations and consist of on-source profiles of the $^{13}$C$^{16}$O($J = 2 − 1$) line, which has a rest frequency of 230.538 GHz (1.3 mm). The baseline length spans over 26–370 m (C array), 11–148 m (D array), and 8.5–66 m (E array) providing HPBWs of 0$''$.9, 2$'$.1, and 4$'$.4, respectively, at 1.3 mm. The HPBW of the individual 10.4 mm antennas is ∼32$''$ at the observed frequency.

The CARMA correlator takes measurements in three separate bands, each having an upper and lower sideband. One band was set to the low-resolution 468 MHz bandwidth mode (15 channels of 31.25 MHz each) to observe continuum emission and was centered on the line. The other two bands were configured with 62 MHz and 31.5 MHz bandwidth across 63 channels (with a resolution of 1.3 km s$^{-1}$ and 0.65 km s$^{-1}$, respectively) and were also centered on the line. The line was measured in the upper sideband in the C and E array and in the lower sideband in the D array.

Bandpass and phase calibration were performed using 3C120 and 0530+135. 0532+075 was used as a secondary phase calibrator to determine the quality of the phase transfer from the primary phase calibrator. The observing sequence was to integrate on the primary phase calibrator for ∼2.5 minutes, the target for ∼18 minutes, and the secondary phase calibrator for ∼2.5 minutes. The cycle was repeated for each track, which lasted between 1.5 hr and 5 hr. Absolute flux calibration was carried out with 0530+135 and 3C120 using the continuously updated CARMA flux catalog to obtain their flux values at each observation.

The raw data were smoothed by a Hanning filter within MIRIAD$^7$ and then exported into FITS format so that it could be analyzed with the CASA$^8$ data reduction package. All calibration and imaging was carried out within CASA. The image cubes were multiscale CLEANed down to the 3σ threshold using natural weighting and were corrected for primary beam attenuation. The multiscale algorithm (Rich et al. 2008) within CASA was set to four unique scales; the largest corresponding to the largest structures visible in individual channel maps. Each scale was approximately set to three times smaller than the preceding scale.

Each of the three CARMA configurations sample a different range of spatial frequencies, the range of which is dependent upon the maximum and minimum baselines ($b_{\text{max}}$ and $b_{\text{min}}$) of each configuration. The sources we are observing are extended and therefore it is necessary to consider the response of each CARMA configuration to this extended emission. For any array configuration, emission with angular scales of $\sim\lambda/b_{\text{min}}$ or greater is not reproduced in the maps (Taylor et al. 1999) and this scale is often used as a guide for the resolving out scale or maximum scale of an array configuration. To obtain a more robust estimate of the largest angular scale that can be accurately imaged in the high spatial resolution C configuration maps, we computed the visibilities of an extended emission feature (whose spatial extent was set to that of the primary beam) using CASA as simulation tool, simdata. This tool then produced a CLEANed image of these visibilities from which we calculated the resolving out scale to be ∼6$''$ (i.e., 0.6$''$/b$_{\text{min}}$). Ultimately, combining the data from these three configurations allows the missing short spacings from the extended C configuration to be recovered while maintaining its high spatial resolution.

3. RESULTS

Betelgeuse is a semi-regular variable and its radial velocity exhibits variability on timescales ranging from short 1.5 year periods as suggested by Stebbins & Huffer (1931) to longer 5.8 year periods (Spencer Jones 1928). Its radial velocity amplitudes are also known to vary by at least ±3 km s$^{-1}$ (Smith et al. 1989) making it difficult to determine a precise value for the stellar center-of-mass radial velocity. In this study we adopt a heliocentric radial velocity of +20.7 km s$^{-1}$ ($v_{\text{lsr}}$ = 4.8 km s$^{-1}$); a value adopted by Harper et al. (2008) and is based on the mean values of Spencer Jones (1928) and Sanford (1933). All spectra are plotted with respect to the stellar center-of-mass rest frame.

3.1. CO($J = 2 − 1$) Spectra

The spectrum for each individual configuration image cube (which are composed of all the appropriate configuration tracks listed in Table 1) along with the multi-configuration image cube can be used to obtain information on the kinematics of the S1 and S2 flows. The spectra corresponding to the C, D, and E configuration image cubes are plotted in Figure 1 for both the high (0.65 km s$^{-1}$ bin$^{-1}$) and low (1.3 km s$^{-1}$ bin$^{-1}$) spectral resolution data and were obtained by integrating all emission within a circular area of radius 5$''$ centered on the source. The high and low spectral resolution modes allow two independent sets of spectra to be measured for each observation and thus provide a good check on the data quality. The high-resolution spectra (channel width = 0.65 km s$^{-1}$) give the best measure

---

$^7$ Multichannel Image Reconstruction, Image Analysis and Display, http://www.atnf.csiro.au/computing/software/miriad/.

$^8$ Common Astronomy Software Applications, http://casa.nrao.edu/.
Table 1

| Observation Date | Configuration | Time on Source (hr) | Flux Calibrator | Phase Calibrators | Image Cube Dynamic Range |
|------------------|---------------|---------------------|-----------------|-------------------|-------------------------|
| 2007 Jun 18      | D             | 0.9                 | 0530+135        | 0530+135, 0532+075 | 22.8                    |
| 2007 Jun 21      | D             | 3.0                 | 0530+135        | 0530+135, 0532+075 | 22.7                    |
| 2007 Jun 24      | D             | 2.1                 | 0530+135        | 0530+135, 0532+075 | 26.1                    |
| 2007 Jun 25      | D             | 2.4                 | 0530+135        | 0530+135, 0532+075 | 30.2                    |
| 2009 Jul 7       | E             | 3.2                 | 3C120           | 3C120, 0532+075   | 30.1                    |
| 2009 Nov 5       | C             | 1.2                 | 3C120           | 3C120, 0532+075   | 17.3                    |
| 2009 Nov 9       | C             | 3.0                 | 3C120           | 3C120, 0532+075   | 27.2                    |
| 2009 Nov 15      | C             | 1.0                 | 3C120           | 3C120, 0532+075   | 17.8                    |
| 2009 Nov 16      | C             | 3.2                 | 3C120           | 3C120, 0532+075   | 32.0                    |
| All              | C             | 8.4                 |                 |                   | 43.8                    |
| All              | D             | 8.4                 |                 |                   | 31.9                    |
| All              | Multi-configuration | 20.0          |                 |                   | 52.3                    |

Notes.

a Low spectral resolution (i.e., channel width of 1.3 km s\(^{-1}\)).

b The peak emission of the image cube divided by the root mean square of the residual image.

The E configuration image cube spectrum has a total line width of 29.2 km s\(^{-1}\) and the low spectral resolution profile contains a steep blue wing emission feature between \(-16.0\) km s\(^{-1}\) and \(-11\) km s\(^{-1}\) and a more flat-topped feature between \(-10.3\) km s\(^{-1}\) and \(-13.2\) km s\(^{-1}\). This steep emission wing shows that the turbulence in the flow is less than or equal to the velocity bin size. The blue wing in the high-resolution profile matches the lower resolution profile well but the remainder of the profile looks more complex than the flat-topped feature seen in the lower resolution profile. The profile shape of the CO(J = 2 - 1) line has been well documented by previous single-dish observations (e.g., Knapp et al. 1980; Huggins 1987) and, out of our three individual configuration spectra, we expect the most compact E configuration spectra to resemble these single-dish measurements the closest due to its better sampling of the inner u - v plane and consequent sensitivity to extended structures. This indeed turns out to be the case when we compare our three individual configuration spectra to those previous single-dish profiles. The blue wing emission feature appears again in the D configuration spectrum at the same velocities as those in the E configuration spectrum but the remainder of the profile appears quite different. Between \(-10.3\) km s\(^{-1}\) and \(+13.2\) km s\(^{-1}\), the D configuration spectrum is dominated by a blue wing at \(-10.0\) km s\(^{-1}\), a red wing at \(+13.0\) km s\(^{-1}\), and an emission feature at \(-0\) km s\(^{-1}\).

The line profile has a much lower flux in the high spatial resolution C configuration spectrum due to its lack of sensitivity to extended structure. The blueshifted emission feature located between \(-16.0\) km s\(^{-1}\) and \(-11.0\) km s\(^{-1}\) in the E and D configuration spectra is almost completely spatially filtered by the extended C configuration. This component of the line has previously been associated with the outer S2 flow (Huggins 1987) and as the majority of it has been spatially filtered by our C configuration we expect even less contribution from the S2 flow at lower absolute velocities still. For the redshifted line emission we again expect the majority of the S2 contribution to be spatially filtered, so we conclude that the majority of the emission in the C configuration spectrum emanates from the inner S1 flow. The spectrum is double peaked with the blue- and redshifted wings extending to \(-9.0\) km s\(^{-1}\) and \(+10.6\) km s\(^{-1}\), respectively, and we define these as the outflow velocities of S1. As discussed in Section 2, the C configuration has a resolving

![Figure 1](https://example.com/figure1.png)

Figure 1. Spectra integrated over a radius of 5" for each array configuration image cube. The blueshifted emission component between \(-16.0\) km s\(^{-1}\) and \(-10.0\) km s\(^{-1}\) is almost resolved out in the C configuration image cube spectrum. The red and blue lines correspond to the high and low spectral resolution data, respectively. (A color version of this figure is available in the online journal.)

of S1 and S2 kinematics and therefore all outflow velocities are derived from these spectra.
out scale of $\sim$6" at 1.3 mm and so is not sensitive to angular scales larger than this. If the emission between $-9.0 \text{ km s}^{-1}$ and $+10.6 \text{ km s}^{-1}$ in the C configuration spectrum appeared as a flat-topped profile then we could conclude that the S1 flow lies within a radius of 3" from the star. Clearly, however, the lower absolute velocity components of this profile have been spatially filtered so we conclude that the radial extent of the S1 from the star is greater than 3". If we assume that the S1 flow would produce a top-hat line profile were it not for the resolving out effects of the interferometer, then its integrated line flux is $3.1 \times 10^{-19} \text{ W m}^{-2}$.

To obtain the most robust value for the S2 outflow velocities we examine the high spectral resolution multi-configuration image cube spectrum, which is composed of all tracks from all three configurations. It is worth stressing that by analyzing the multi-configuration image cube we make the assumption that the physical properties of all three components (i.e., α Ori, S1, and S2) have not changed over the total observation period (i.e., $\sim$2.5 yr). The profile is found to have a total line width of 28.6 $\pm$ 0.7 km s$^{-1}$, which is in close agreement with previous single-dish observations of the line where values of 30.6 $\pm$ 2.5 km s$^{-1}$ and 28.6 km s$^{-1}$ were reported by Knapp et al. (1980) and Huggins (1987), respectively. The centroid velocity of the spectrum is $-1.1 \pm 0.7 \text{ km s}^{-1}$ ($v_{\text{lsr}} = 3.7 \pm 0.7 \text{ km s}^{-1}$), which is again in close agreement with Knapp et al. (1980) and Huggins (1987) values of $v_{\text{lsr}} = 3.0 \pm 2.5 \text{ km s}^{-1}$ and $v_{\text{lsr}} = 3.7\pm0.4 \text{ km s}^{-1}$, respectively. The integrated line flux is $1.5 \times 10^{-17} \text{ W m}^{-2}$ of which approximately 20% emanates from the S1 flow.

The outflow velocities of S2 are $-15.4 \text{ km s}^{-1}$ and $+13.2 \text{ km s}^{-1}$ which, like the S1 flow, are slightly asymmetric but in the opposite sense. Note that the S1 and S2 outflow velocities are dependent on the adopted radial velocity of Betelgeuse. If, for instance, we instead adopt a radial velocity of 21.9 km s$^{-1}$ (Famaey et al. 2005) then the S2 outflow velocities become even more asymmetric ($-16.6 \text{ km s}^{-1}$ and $+12.0 \text{ km s}^{-1}$) while the S1 outflow becomes less so ($-10.2 \text{ km s}^{-1}$ and $+9.4 \text{ km s}^{-1}$). Both S1 and S2 therefore cannot have spherically symmetric outflow velocities regardless of the adopted stellar radial velocity. Adopting a mass of 18 $M_{\odot}$ and a radius of 950 $R_{\odot}$ (Harper et al. 2008) then the escape velocity for Betelgeuse is 85 km s$^{-1}$, which is much greater than the S1 and S2 outflow velocities. This indicates that the majority of the stellar mass-loss mechanism’s energy goes into lifting the CO molecules out of the gravitational potential and not into their outflow velocities. These outflow velocities are greater than the adiabatic hydrogen sound speed, which, if we assume that the gas temperature is the same as the excitation temperature, are $1.7 \text{ km s}^{-1}$ and $1 \text{ km s}^{-1}$ for S1 and S2, respectively.

The spectra in Figure 2 are taken from the low-resolution multi-configuration image cube using circular extraction areas ranging in radius from 1'' to 10'' and demonstrate how the line profile changes over these different extraction areas. The most striking change in the line profile is the change in appearance of the extreme blue wing. At small extraction radii where we sample the most compact emission, the feature is weak in comparison with the rest of the line but becomes more dominant as we begin to sample more of the extended emission. This indicates that even the high absolute velocity components of the S2 flow have extended emission and this is why they are almost completely spatially filtered by CARMA’s C configuration. The large reduction of flux at $-11 \text{ km s}^{-1}$ suggests that there is more material moving toward the observer than at other lower absolute velocities indicating a non-isotropic (or non-spherical) S2 flow. This suggests a more sheet-like (flatter) structure rather than a spherical cap.

3.2. Multi-configuration Image Cube

A subset of the blueshifted velocity channel maps of the low spectral resolution multi-configuration image cube is presented in Figure 3. The first channel map at $-17.9 \text{ km s}^{-1}$ shows just the compact unresolved continuum emission with no extended emission present. Between $-16.7 \text{ km s}^{-1}$ and $-9.0 \text{ km s}^{-1}$, we see evidence for the development of a classical shell signature for the S2 flow. We first sample the highest velocity components where the emission is relatively compact (i.e., between $-16.7 \text{ km s}^{-1}$ and $-12.9 \text{ km s}^{-1}$) and then sample lower radial velocity components where S2 becomes a faint ring (i.e., between $-11.6 \text{ km s}^{-1}$ and $-9.0 \text{ km s}^{-1}$). At lower velocities again, these rings disappear into the noise of the maps and possibly extend out beyond the primary beam at zero velocity when the rings should have maximum spatial extent. The emission from the channel maps between $-15.3 \text{ km s}^{-1}$ and $-11.6 \text{ km s}^{-1}$ corresponds to all the emission in the extreme blue wing component of the multi-configuration image cube line profile discussed in Section 3.1. We can see in Figure 3 that all of this emission is greater than the C configuration resolving out scale, therefore confirming that our C configuration line profile is mainly composed of S1 emission. The shell formation signature of S2 is also apparent in the redshifted velocity channel maps between $+7.5 \text{ km s}^{-1}$ and $+13.8 \text{ km s}^{-1}$ but the emission appears weaker and the rings fainter therefore indicating that S2 is somewhat fragmented.

The multi-configuration maps also show the central compact emission from the S1 flow at velocities between $-10.3 \text{ km s}^{-1}$ and $+11.3 \text{ km s}^{-1}$. This S1 emission can be seen in the final two maps of Figure 3 as a central slightly elongated emission.
feature surrounded by the fainter rings of the S2 flow. In the maps where both S1 and S2 are present the emission from S1 appears brighter than the emission from S2. The spatial extent of the S1 flow varies from channel map to channel map but appears to be larger than the 2′′ value given by Smith et al. (2009), who observed off-star wind scattered ro-vibration CO lines.

3.3. Determination of the S1 and S2 Radii

The spatial extent of the S1 and S2 flows around Betelgeuse was not directly determined from either the CO infrared absorption spectra of Bernat et al. (1979) or previous CO single-dish radio observations (Knapp et al. 1980; Huggins 1987; Huggins et al. 1994). Our low spectral resolution multi-configuration image cube has sufficient spatial resolution and signal to noise to make direct estimates of the maximum radius of both flows. The outer S2 flow is not seen in the low absolute velocity channel maps where its spatial extent is maximum and either lies outside of the primary beam or is lost into the noise near the edge of the maps. We derive the maximum outer scale of the S2 flow by looking at the spatial scales of the S2 flow in the higher absolute velocity maps where S2 is present. If we assume that S2 is spherically symmetric with an outer radius $R_{S2}$, and is undergoing steady expansion with velocity $V_{S2}$, then we can estimate its radius in each velocity channel using the following relation:

$$r_{\text{chan}} = R_{S2} \sin \left[ \frac{\cos^{-1} \left( \frac{v_{\text{chan}}}{V_{S2}} \right)}{R_{S2}} \right],$$

where $r_{\text{chan}}$ is the S2 radius in a channel at velocity $v_{\text{chan}}$. 

![Figure 3. Eight channel maps from the multi-configuration image cube ($\Delta v = 1.3$ km s$^{-1}$). The peak emission has been cut at 0.2 Jy beam$^{-1}$ to emphasize the fainter emission. The color scale is linear and has been normalized to this maximum cutoff and minimum value of each channel. The contour levels are at $-2\sigma$, $2\sigma$, $4\sigma$, and $6\sigma$ ($1\sigma \sim 0.03$ Jy beam$^{-1}$ but varies per channel). Dashed green lines represent negative contours. (A color version of this figure is available in the online journal.)](image)

![Figure 4. Integrated intensity image of the D configuration channel maps that contain the discrete second source approximately 5′′ S–W of α Ori. Contours for the integrated intensity are $1\sigma$, $1.5\sigma$, $2\sigma$, and $3\sigma$ ($1\sigma = 1.3$ Jy beam$^{-1}$ km s$^{-1}$). The size of the restoring beam is shown in white in the bottom left corner. (A color version of this figure is available in the online journal.)](image)
Figure 5. Derived S2 radius as a function of velocity (red points) overplotted with two model outflows. The blueshifted model (left) corresponds to an outflow with a maximum radius of 17′′ and a velocity of 16.7 km s\(^{-1}\) while the redshifted model (right) corresponds to an outflow with a maximum radius of 16′′ and a velocity of 13.8 km s\(^{-1}\). Note: the line profile is 1.9 km s\(^{-1}\) wider in the low-resolution image cube (\(\Delta v = 1.3 \text{ km s}^{-1}\)) than in the high-resolution image cube.

(A color version of this figure is available in the online journal.)

We use Equation (1) to estimate the maximum projected spatial extent of S2 that occurs at zero velocity. An estimate of the S2 radius per channel (\(r_{\text{chan}}\)) was found by creating annuli of increasing radius around the central emission in each relevant line channel map of the multi-configuration image cube, extracting all flux within each annulus and then plotting these fluxes against distance from the star for each channel. The maximum of these resultant curves was then deemed to be the maximum radius of S2 per channel. Figure 5 shows these data overplotted with two model outflows that were created using Equation (1). The blueshifted data points were best fitted by a model outflow of maximum radius 17′′ and outflow velocity 17 km s\(^{-1}\), while the redshifted data points were best fitted by a model outflow of maximum radius 16′′ and outflow velocity 14 km s\(^{-1}\). It is worth mentioning that this estimate for the spatial extent of S2 is only weakly dependent on our adopted radial velocity value for Betelgeuse and adopting a slightly different value would simply alter S2’s outflow velocities. As S2 is not present in our lowest absolute velocity map we are not able to report an estimate of its width.

In the left column of Figure 6 we investigate the intensity distribution of CO emission as a function of projected radius, \(R\), for both the S1 and S2 flows. From our discussions in Section 3.1 we can assume that all line emission between \(-15.4 \rightarrow -10.3 \text{ km s}^{-1}\) and \(+12.4 \rightarrow +13.8 \text{ km s}^{-1}\) emanates solely from the S2 flow. Using the low spectral resolution multi-configuration image cube we integrate the surface brightness over these channels and find that the intensity falloff is proportional to \(R^{-1}\) (Figure 6, top). To investigate the S1 flow intensity distribution around α Ori we integrate the surface brightness over the channels between \(-9.0 \rightarrow +11.3 \text{ km s}^{-1}\). Although these channels contain emission from both S1 and S2, most of the S2 emission here will have larger projected radii and thus the intensity proportional to \(R^{-2}\) is also shown for comparison. Right column: the corresponding visibility amplitude as a function of \(u - v\) distance (\(q\)) of both outflows can be modeled well by an \(R^{-1}\) falloff in intensity. The error bars in all plots represent the standard error of the mean.

(A color version of this figure is available in the online journal.)
majority of the inner emission should emanate from the S1 flow. Between 0′.5 and 4″ from the star the intensity is again found to be proportional to \( R^{-1} \) (Figure 6, bottom). Such an intensity distribution is expected for an optically thin homogeneous constant velocity outflow with \( \rho \propto 1/R^2 \). Beyond 4″ the intensity falloff is more rapid and is close to an \( R^{-2} \) distribution, which may mark the initiation of the current epoch of mass loss.

Insight can also be gained into how the intensity varies on different size scales by conducting analysis in the \( u-v \) plane and plotting the visibility amplitude of \( \alpha \) Ori against \( u-v \) distance. The result of this is shown in the right column of Figure 6 where the same channels corresponding to the S1 and S2 flows have been used. The data are azimuthally averaged, and have been binned to produce one data point per k\( \lambda \). The result for both the S1 and S2 data is a steep drop-off in visibility amplitude over a relatively short \( u-v \) distance, signaling that the sources are well resolved. Both sets of visibility data agree with an intensity proportional to \((a^2 + R^2)^{-1/2}\), where \( a \) is an inner spatial limit. This is because the Hankel transform of this function is \( q^{-1}e^{-2\pi aq} \) (Bracewell 2000), where \( q \) is the \( u-v \) distance, and a vertically scaled version of this function is shown to match the visibility data very well in Figure 6. As analysis in both the sky and \( u-v \) plane indicate the intensities of both flows are proportional to \( R^{-1} \) we conclude that when azimuthally averaged, both outflows are consistent with an optically thin and quasi-steady flow that is in agreement with Smith et al. (2009; i.e., S1) and Plez & Lambert (2002; i.e., S2).

An exact determination of the maximum spatial extent of the S1 flow is more difficult as we do not see the classical shell formation signature for it as we sample across velocities, like S2. Instead its spatial extent varies over the channel formation signature for it as we sample across velocities, like S1 flow is more difficult as we do not see the classical shell quasi-steady flow that is in agreement with Smith et al. (2009; averaged, both outflows are consistent with an optically thin and electron–atom bremsstrahlung and possibly dust emission, so it is not unreasonable to also expect variability at millimeter-wavelengths too. The D configuration data were acquired under adverse weather conditions and these data have the highest noise levels out of the three configurations. Its continuum emission measurement is approximately 50% greater than the C and E configuration continuum measurements, which were also acquired approximately two years after the D configuration data. We believe that the continuum emission derived from the multi-configuration image cube is a reasonable estimation of the mean millimeter-continuum flux density over the two-year period and is in reasonably good agreement with the 250 GHz flux density of Altenhoff et al. (1994) who report a mean value of 351 ± 25 mJy for 1986 → 1989.

4. DISCUSSION

4.1. Previous CO Observations

Bernat et al. (1979) were the first to detect circumstellar absorption lines in CO by looking at the fundamental ro-vibration lines at 4.6 \( \mu \)m. These infrared observations revealed two separate outflows around \( \alpha \) Ori; an excited \((T_{\text{exc}} = 200 \text{ K})\) S1 flow with an expansion velocity of 9 km s\(^{-1}\) and a less excited \((T_{\text{exc}} = 70 \text{ K})\) S2 flow moving with a faster expansion velocity of 16 km s\(^{-1}\). Knapp et al. (1980) were the first to detect emission in the \( CO(J = 2 - 1) \) line at 1.3 mm using the 10 m millimeter-wave telescope at OVRO but only detected one component expanding at 15 km s\(^{-1}\). By analyzing the shape of the line profile, they concluded that the S2 radius of 55″ derived by Bernat et al. (1979) was too large and that it lies at a radius of \( R \lesssim 10″ \). Since the detection by Knapp, a number of observations at 1.3 mm have been carried out with various beam sizes and all spectra look remarkably similar; that is the profile has a steep extreme blueshifted emission component with the remainder of the profile looking more flat topped and containing a number of less dominant spikes. Huggins (1987) used their single-dish observations (HPBW \sim 32″) of the \( CO(J = 2 - 1) \) line along with excitation and self-shielding models of CO to conclude that the S1 flow makes little contribution to the final emission line. They also identify the extreme blue wing of the line with the S2 flow and predict that it may extend out to a radius of \sim 16″. Later, however, Huggins et al. (1994) compared their detected 609 \mu \text{m} P_1 \rightarrow 3 P_0 \) fine structure line of C\textsc{i} with CO data obtained with the IRAM 30 m telescope (HPBWs \sim 12″) and find that the expansion velocities in both lines are essentially the same. They conclude that the radial

| Configuration   | Restoring Beam (″ × ″) | Flux (mJy) | Uncertainty (mJy) |
|-----------------|------------------------|------------|-------------------|
| C               | 0.96 × 0.76            | 234        | 18                |
| D               | 2.33 × 1.87            | 389        | 72                |
| E               | 4.93 × 3.84            | 278        | 40                |
| Multi-configuration | 1.05 × 0.84         | 289        | 21                |

In Table 2 we show the derived continuum flux densities for each of the three configuration image cubes and also the multi-configuration image cube. The high spectral resolution \( (\Delta v = 0.65 \text{ km s}^{-1}) \) image cubes were just wide enough to image the CO line but were too narrow to make accurate estimates of the continuum flux density. Therefore, all continuum flux density estimates are derived from the lower spectral resolution \( (\Delta v = 1.3 \text{ km s}^{-1}) \) image cubes from which we were able to
extent of C i is \( \lesssim 7'' \) and both the CO and C i are formed in the inner envelope and roughly extend over the same area.

The shape of our multi-configuration line profile for extraction areas of radii 6'' or greater is in good agreement with previous high signal-to-noise single-dish CO(J = 2 − 1) spectra (e.g., Huggins et al. 1994, Figure 1) although the emission spikes in our line profiles are more dominant. Our total line width of 28.6 km s\(^{-1}\) is in good agreement with Huggins (1987) and Huggins et al. (1994), who report line widths of 28.6 km s\(^{-1}\) and 30 km s\(^{-1}\), respectively. The extreme blue wing in both of these spectra is the dominant emission feature of the line and this is also true in our multi-configuration spectra at extraction areas \( \gtrsim 6'' \). Using the IRAM 30 m telescope, which has an HPBW of only 12'' at 230 GHz, Huggins et al. (1994) produce a similar line profile shape to that presented in Huggins (1987), who have a larger HPBW of \( \sim 30'' \). From this, one would expect that the majority of the blue wing emission is compact; however, our multi-configuration line profiles suggest otherwise, and show a continuous increase in the blue wing emission as we take larger extraction regions out to 10''.

The multi-configuration maps also show a faint ring structure forming at \( \sim 11.6 \) km s\(^{-1}\) and expanding further out in lower absolute velocity channel maps. This ring emission is fainter than the higher velocity compact emission so we see a drop in flux density in our spectra at the point where these rings form. Therefore, the steepness of the extreme blue wing in our multi-configuration spectrum means that there is merely more CO emitting at higher velocities than at lower velocities, which is indicative of a sheet-like structure moving toward the observer.

The line profiles of higher CO rotational transitions for Betelgeuse have been published in Kemper et al. (2003) and De Beck et al. (2010). De Beck et al. (2010) present high spectral resolution (0.3125 MHz) line profiles for the CO(J = 2 − 1), (J = 3 − 2), and (J = 4 − 3) transitions that were obtained with the James Clerk Maxwell Telescope (JCMT). For the CO(J = 2 − 1) transition the JCMT has an HPBW of \( \sim 20'' \) and the profile appears similar to our multi-configuration profile over the same flux density extraction area (i.e., Figure 2), with the extreme blue wing component being the dominant feature in both. This feature, which is emission from the S2 flow, becomes a less dominant component of the line profile at the higher CO(J = 3 − 2) and CO(J = 4 − 3) transitions where the JCMT has an HPBW of \( \sim 13'' \) and \( 8'' \), respectively, and does not capture all of the S2 emission, which is shown in Figure 3 to be extended at these velocities. Also, the higher rotational states (J \( \approx 10 \)) will be populated more by the higher excitation temperature \( \sim 200 \) K S1 flow so these line profiles become dominated by emission from the slower S1 flow. This is confirmed by our narrow SOFGREAT CO(J = 12 − 11) line profile that is presented in the Appendix of this paper, and also by a visual inspection of Herschel-HIFI archival line profiles of the CO(J = 6 − 5), (J = 10 − 9), and (J = 16 − 15) transitions.

The CO 4.6 \( \mu \)m ro-vibration lines have been observed with the Phoenix spectrograph (Hinkle et al. 1998) by Ryde et al. (1999) and Smith et al. (2009) on the 2.1 m telescope at Kitt Peak and on the 8 m Gemini South telescope, respectively. By assuming a Boltzmann population distribution for the ground rotational levels of CO, Ryde et al. (1999) derived a mean excitation temperature of 38\(^{+6}_{-5}\) K along the line of sight at a projected distance of 4'' north of Betelgeuse. Our CARMA data suggest that the S1 flow extends out to approximately this distance but Ryde et al.’s temperature is not in agreement with either of the line-of-sight S1 or S2 excitation temperatures of 200\(^{+50}_{-30}\) K and 70 \( \pm 10 \) K derived by Bernat et al. (1979). This discrepancy may indicate that the excitation is quite non-uniform. Smith et al. (2009) did not derive an excitation temperatures but used their 4.6 \( \mu \)m spectra to reveal extended resonantly scattered CO emission out to \( \sim 2'' \), a factor of two smaller than our S1 radius. They observe emission over a velocity range of 30 km s\(^{-1}\) but two distinct flows are not detected. Mild \( \sim (20\%) \) density inhomogeneities are reported but overall, their observations are consistent with an optically thin and steady wind which is consistent with our findings.

4.2. K\( i \) 7699 \( \AA \) Spectra

The S2 flow was first identified in high-resolution K i and Na i absorption spectra by Goldberg et al. (1975) and subsequently re-observed multiple times over the next couple of years (Goldberg 1979). It is interesting to compare these and Bernat et al.’s (1979) CO line-of-sight absorption velocities with those from the CARMA emission spectra obtained at similar spectral resolutions and also to measure, the perhaps co-spatial line broadening of the K i S2 absorption feature.

We have obtained K\( i \) 7698.98 \( \AA \) spectra using the cross-dispersed echelle spectrometers on the Harlan J. Smith 107 inch (2.7 m) reflector at McDonald Observatory. With 2 pixels per resolution element an R = \( \lambda/\Delta \lambda \approx 200,000 \) and an R = 500,000 spectrum were obtained on 2007 March 25 and April 13, respectively. The spectra were wavelength calibrated with ThAr lamp lines and the lower resolution spectrum was checked by fitting six symmetric terrestrial O\( _2 \) lines in the same order using wavelengths from Babcock & Herzberg (1948). The O\( _2 \) lines confirmed that the R = 200,000 calibration was good to better than 0.1 km s\(^{-1}\). Upon cross-correlating the low-and high-resolution spectrum the high-resolution spectrum appeared redshifted by 0.60 km s\(^{-1}\), i.e., one resolution element, for which we do not have an explanation except to note that a similar offset has been reported by Welty et al. (1994). We use the cross-correlation to define the wavelength calibration of the R = 500,000 spectrum and we adopt a systematic error of \( \sigma_{\text{sys}} = 0.2 \) km s\(^{-1}\).

The high-resolution spectrum is shown in Figure 7 in the adopted stellar center-of-mass rest frame (\( V_{\text{rad}} = \ldots \)
The K$_1$ spectrum also reveals a slight inflection in the observed line profile at $+3.6$ km s$^{-1}$ (heliocentric), which may represent structure in the underlying photospheric profile or additional absorption in which case it has $\sim0.1$ the column density of S$_2$ ($N_{K_1-S_2} \approx 1.2 \times 10^{11}$ cm$^{-2}$). The S$_2$ absorption velocity minima can be compared to those obtained by Goldberg (1979, Figure 7) who measured values between 1975 and 1978 of $4.2 \pm 0.2$ and $5.0 \pm 0.2$ km s$^{-1}$ and these differences may result from changes caused by radial velocity changes in the underlying photospheric spectrum. Bernat et al.’s (1979) CO IR absorption observations reveal S$_2$ heliocentric velocities of $+4.94 \pm 0.30$ km s$^{-1}$ (1979 March 6) and $+4.60 \pm 0.04$ km s$^{-1}$ (1979 April 14) with turbulent velocities of 4 and 1 km s$^{-1}$ for the S$_1$ and S$_2$ features, respectively.

In terms of the center-of-mass radial velocity of the star our K$_1$ feature implies an outflow velocity of $+15.6$ km s$^{-1}$. The blue edge of our CARMA multi-configuration CO profile is estimated to be $+15.4$ km s$^{-1}$, which suggests a dynamical association with the CO S$_2$ flow and very close agreement with Bernat et al.’s (1979) CO absorption velocities listed above. Plez & Lambert (2002) have also estimated the radius and velocity of the suspected K$_1$ S$_2$ flow using $R = 110,000$ resolution long-slit spectra. They found a geometrically thin shell (1") with velocity of $V_{\text{shell}} = 18 \pm 2$ km s$^{-1}$ with a radius of 55", which is much larger than the field of view of the CARMA spectra. Their long-slit spectra show several smaller partial shells but it is not simple to directly associate the CO emission feature with one or more of these shells especially given the uncertainty in the ionization balances of CO and K$_1$. It is possible that the 55" shell is associated with the inflexion caused by additional absorption (and low column density) at a velocity slightly higher then S$_2$ observed in our K$_1$ profile.

5. CONCLUSIONS

The two distinct velocity components seen by Bernat et al. (1979) in CO absorption against the stellar spectrum at 4.6 $\mu$m have both been detected at 230 GHz for the first time. The first velocity component known as S$_1$ has an expansion velocity of 9 km s$^{-1}$ (Bernat et al. 1979) and is detected in our high spectral resolution C configuration profile with the same blueshifted velocity (i.e., $-9.0$ km s$^{-1}$) and with a larger redshifted outflow velocity of $+10.6$ km s$^{-1}$. The extended CARMA C configuration has a resolving out scale of $\sim6''$ and thus spatially filters almost all of the S$_2$ emission leaving us with an approximate spectrum for the S$_1$ flow. An extreme blue wing of the CO spectrum appears in the D and E configuration spectra, which we associate with the S$_2$ flow. The high spectral resolution multi-configuration spectrum is used to determine S$_2$ outflow velocities of $-15.4$ km s$^{-1}$ and $+13.2$ km s$^{-1}$, which are in good agreement with our K$_1$ 7699 Å line-of-sight S$_2$ velocity and that reported by Bernat et al. (1979).

The low spectral resolution multi-configuration maps provide the first direct measurements on the spatial extent of the S$_2$ flow, which we derive to have a radius of 17", a value that is higher than most previous estimates. We do not see a well-defined outer edge for the S$_1$ flow but believe that it may extend out to a radius of $\sim4''$. Previous single-dish observations of the CO line with small HPBW do not show the classical resolved signature of high emission at large absolute velocities and low emission at low absolute velocities for two main reasons. First, the S$_1$ flow is still unresolved in these single-dish observations and thus contributes emission and at the lower absolute velocities. As well as this, the multi-configuration CARMA maps show that the S$_2$ emission is brighter in the higher absolute velocity maps than at lower absolute velocities and so when the emission from the fainter rings is neglected (i.e., when observed with a small HPBW), the overall line profile does not change significantly.

Assuming a mean outflow velocity of 14.3 km s$^{-1}$ and 9.8 km s$^{-1}$ for the S$_2$ and S$_1$ flows, respectively, then their ages are $\sim1100$ yr and $\sim380$ yr. Since Plez & Lambert (2002) have detected K$_1$ out to 55" at a similar velocity to the CO S$_2$ flow, then, assuming the CO and K$_1$ are coupled, there appears to be little or no further acceleration in Betelgeuse’s outflow once the S$_2$ flow begins (which is somewhere greater than 4\). The composition and dynamics of the interface between S$_1$ and S$_2$ remain unknown and future instruments such as the Atacama Large Millimeter/submillimeter Array (ALMA) will provide a greater understanding of this region. Higher spatial resolution, increased sensitivity, and excellent $u-v$ coverage are needed to determine whether the inner S$_1$ flow is discrete or just an extension of the current wind phase. Our SOFIA–GREAT spectrum shows that the higher excitation gas traces the slower S$_1$ component, and therefore the high-frequency bands of ALMA will preferentially trace the S$_1$ flow. Solutions to these remaining puzzles will broaden our knowledge of the evolutionary aspect of Betelgeuse’s outflow and shed light into the driving mechanisms of M supergiant winds.

Support for CARMA construction was derived from the states of California, Illinois, and Maryland, the James S. McDonnell Foundation, the Gordon and Betty Moore Foundation, the Kenneth T. and Eileen L. Norris Foundation, the University of Chicago, the Associates of the California Institute of Technology, and the National Science Foundation. Ongoing CARMA development and operations are supported by the National Science Foundation under a cooperative agreement, and by the CARMA partner universities. This work is based (in part) on observations made with the NASA/DLR Stratospheric Observatory for Infrared Astronomy. SOFIA Science Mission Operations are conducted jointly by the Universities Space Research Association, Inc., under NASA contract NAS2-97001, and the Deutsches SOFIA Institut unter DLR contract 50 OK 0901. GREAT is a development by the MPI für Radiointomie and the KOSMA/Universität zu Köln, in cooperation with the MPI für Sonnensystemforschung and the DLR Institut für Planetenforschung. We thank Sarah Kennelly for providing us with archival Herschel spectra. This publication has emanated from research conducted with the financial support of Science
Figure 8. Scaled SOFIA–GREAT CO(\(J = 12 - 11\)) emission line profile binned to 1.3 km s\(^{-1}\) along with the unscaled CARMA C configuration CO(\(J = 2 - 1\)) profile. The star symbol at \(-2.5\) km s\(^{-1}\) marks the location of a weak terrestrial atmospheric emission feature which may contribute to the drop in flux at this velocity in the SOFIA–GREAT line profile.

(A color version of this figure is available in the online journal.)

Foundation Ireland under Grant Number SFI11/RFP.1/AST/3064, and a grant from Trinity College Dublin.

Facilities: CARMA, Smith, and SOFIA

APPENDIX

SOFIA–GREAT OBSERVATION

As part of our larger multi-wavelength study of the CO surrounding Betelgeuse we observed the star (PI: Harper; ID 81_0005_1) with the German Receiver for Astronomy at Terahertz Frequencies (GREAT; Guesten et al. 2000) instrument on NASA and DLR’s Stratospheric Observatory for Infrared Astronomy (SOFIA; Becklin & Gehrz 2009) 2.5 m airborne observatory. The \(^{12}\)\(^{16}\)O(\(J = 12 - 11, 1.38\) THz, 216.9 \(\mu\)m) line was observed to examine the dynamics of the higher excitation S1 component. The observations were made during Flight 86 on 2011 November 10 at 13,100 m (\(\sim 43,000\) ft) when the star had an elevation of 45°. The HPBW was \(\sim 19''\) and the effective on-source exposure time was 12 minutes. Due to technical difficulties during the flight the observations were obtained using a non-standard asymmetric chop sequence with a throw of 60°.

The scaled SOFIA–GREAT emission line profile binned to 1.3 km s\(^{-1}\) is shown in Figure 8 along with the CARMA C configuration CO(\(J = 2 - 1\)) profile, which spatially filters the S2 contribution. This figure shows that the \(J = 12 - 11\) profile reflects the slower moving S1 flow with a width of \(\sim \pm 7.5\) km s\(^{-1}\) approximately centered on the stellar rest frame. This suggests that the \(J = 12 - 11\) emitting plasma is not associated with the faster S2 component and is likely associated with the higher excitation S1 plasma. Owing to uncertainties in the pointing accuracy during our GREAT observation, we defer a discussion of the fluxes to a later time.

REFERENCES

Aipatian, V. S., Ofman, L., Robinson, R. D., Carpenter, K., & Davila, J. 2000, ApJ, 528, 965
Altenhoff, W. J., Thunn, C., & Wendker, H. J. 1994, A&A, 281, 161
Babcock, H. D., & Herzberg, L. 1948, ApJ, 108, 167
Becklin, E. E., & Gehrz, R. D. 2009, in ASP Conf. Ser. 417, Submillimeter Astrophysics and Technology: A Symposium Honoring Thomas G. Phillips, ed. D. C. Lis, J. E. Vaillancourt, P. F. Goldsmith, T. A. Bell, N. Z. Scoville, & J. Znuidzinas (San Francisco, CA: ASP), 101
Bernat, A. P., Hall, D. N. B., Hinkle, K. H., & Ridgway, S. T. 1979, ApJ, 233, L135
Bookbinder, J. A., Stencil, R. E., Drake, S. A., et al. 1987, in Cool Stars, Stellar Systems and the Sun, ed. J. L. Linsky & R. E. Stencel (Lecture Notes in Physics, Vol. 291; Berlin: Springer), 337
Bracewell, R. N. 2000, The Fourier Transform and Its Applications (3rd ed.; Singapore: McGraw-Hill)
Carpenter, K. G., & Robinson, R. D. 1997, ApJ, 479, 970
Danchi, W. C., Bester, M., Degiacomi, C. G., Greenhill, L. J., & Townes, C. H. 1994, AJ, 107, 1469
De Beck, E., Decin, L., de Koter, A., et al. 2010, A&A, 523, A18
Drake, S. A., Bookbinder, J. A., Florkowski, D. R., et al. 1992, in ASP Conf. Ser. 26, Cool Stars, Stellar Systems, and the Sun, ed. M. S. Giampapa & J. A. Bookbinder (San Francisco, CA: ASP), 455
Famaey, B., Jurissen, A., Luri, X., et al. 2005, A&A, 430, 165
Glassgold, A. E., & Huggins, P. J. 1986, ApJ, 306, 605
Goldberg, L. 1979, QJRAS, 20, 361
Goldberg, L. 1984, PASP, 96, 366
Goldberg, L., Ramsey, L., Testerman, L., & Carbon, D. 1975, ApJ, 199, 427
Guesten, R., Hartogh, P., Huebers, H.-W., et al. 2000, Proc. SPIE, 4014, 23
Harper, G. M., Brown, A., & Guinan, E. F. 2008, AJ, 135, 1430
Harper, G. M., Brown, A., & Lim, J. 2001, ApJ, 551, 1073
Harper, G. M., Carpenter, K. G., Kynd, N., et al. 2009, in ASP Conf. Ser. 1094, Cool Stars, Stellar Systems and the Sun, ed. E. Stempels (Melville: NY: AIP), 686
Hartmann, L., & Avrett, E. H. 1984, ApJ, 284, 238
Hinkle, K. H., Cuberly, R. W., Gaughan, N. A., et al. 1998, Proc. SPIE, 3554, 810
Huggins, P. J. 1987, ApJ, 318, 400
Huggins, P. J., Bachiller, R., Cox, P., & Forveille, T. 1994, ApJ, 424, L127
Kemper, F., Stark, R., Justtanont, K., et al. 2003, A&A, 407, 609
Knapp, G. R., & Morris, M. 1985, ApJ, 292, 640
Knapp, G. R., Phillips, T. G., & Huggins, P. J. 1980, ApJ, 242, L25
Lambert, D. L., & Vanden Bout, P. A. 1978, ApJ, 221, 854
Lambert, D. L., & Vanden Bout, P. A. 1978, ApJ, 221, 854
Lambert, D. L., & Vanden Bout, P. A. 1978, ApJ, 221, 854
Lim, J., Carilli, C. L., White, S. M., Beasley, A. J., & Marson, R. G. 1998, Nature, 392, 575
Morton, D. C. 2003, ApJS, 149, 205
Plez, B., & Lambert, D. L. 2002, A&A, 386, 1009
Rich, J. W., de Blok, W. J. G., Cornell, T. J., et al. 2008, AJ, 136, 2897
Ryde, N., Gustafsson, B., Hinkle, K. H., et al. 1999, A&A, 347, L35
Sanford, R. F. 1933, ApJ, 77, 110
Scott, S. L., Amarnath, N. S., Beard, A. D., et al. 2004, in ASP Conf. Ser. 314, Astronomical Data Analysis Software and Systems (ADASS) XIII, ed. F. Ochsenbein, M. G. Allen, & D. Egret (San Francisco, CA: ASP), 768
Smith, M. A., Patten, B. M., & Goldberg, L. 1989, ApJ, 348, 2233
Smith, N., Hinkle, K. H., & Ryde, N. 2009, AJ, 137, 3558
Spencer Jones, H. 1928, MNRAS, 88, 660
Taylor, G. B., Carilli, C. L., & Perley, R. A. (ed.) 1999, in ASP Conf. Ser. 180, Synthesis Imaging in Radio Astronomy II (San Francisco, CA: ASP)
Welty, D. E., Hobbs, L. M., & Kulkarni, V. P. 1994, ApJ, 436, 152
Weymann, R. 1962, ApJ, 136, 844

O’Gorman et al.