The Spectacular BHR 71 Outflow

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Abstract. BHR 71 is a well isolated Bok globule located at ~200 pc, which harbours a highly collimated bipolar outflow. The outflow is driven by a very young Class 0 protostar with a luminosity of $\sim 9\ L_{\odot}$. It is one of a very small number that show enhanced abundances of a number of molecular species, notably SiO and CH_3OH, due to shock processing of the ambient medium. In this paper the properties of the globule and outflow are discussed.

"In the darkness, there'll be hidden worlds that shine"
– Bruce Springsteen, Candy's Room 1977

1 Introduction

In 1977 Arge Sandqvist published a catalogue of southern "dark dust clouds of high visual opacity" (Sanqvist 1977 – 95 entries, numbered 101-195), an extention of an earlier paper with Lindroos (Sandqvist & Lindroos 1976) in which they presented H_2CO absorption line studies of 42 dust clouds (#1-42). Number 136 on Sandqvist's list (Sa 136) is a very opaque Bok globule located near the Coalsack, later catalogued as DC 297.7-2.8 by Hartley et al. (1986) and as entry 71 in the globule list of Bourke, Hyland & Robinson (1995a – BHR 71). Mark McCaughrean in his opening address at this conference highlighted a number of important events that occurred in 1977, in particular IAU Symposium 75 on Star Formation whose proceedings appeared that year. It is fitting that BHR 71, which is featured in a beautiful VLT optical image in the frontpiece (& poster) of these proceedings, can trace its origins in the literature to that same year.

2 Globule properties

The globule properties have been determined by Bourke et al. (1995b, 1997). Spatially and kinematically BHR 71 is associated with the Coalsack at an assumed distance of 200 pc, though it may be as close as 150±30 pc (Corradi et al. 1997). Large scale ^{12}CO & ^{13}CO maps of the globule give a size of ~0.5 pc and mass $40M_{\odot}$, while C^{18}O observations which trace high column density gas imply a size $\sim 0.3 \times 0.15$ pc and a mass of $12M_{\odot}$. The high density (n$>10^4$ cm^{-3}) core traced in ammonia is $\sim 0.2 \times 0.1$ pc in size with a mass of $3M_{\odot}$. The globule velocity is $V_{lsr} \sim -4.5$km s^{-1}.

3 CO Outflow Properties

The properties of the large scale molecular outflow have been determined by B97. As can be seen in Fig. 1, the outflow lobes are well separated on the sky, and extend ~0.3pc

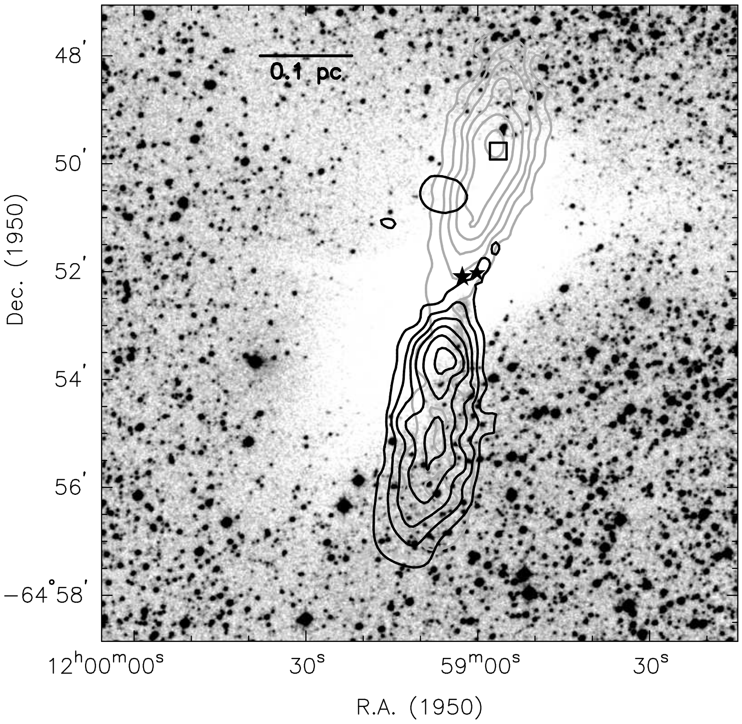

Fig. 1. Digital Sky Survey R-Band image of BHR 71, overlayed with contours of ^{12}CO $J = 1 \rightarrow 0$ emission. The black contours are blue-shifted emission, and the grey contours are red-shifted emission. The two ISO mid-infrared sources are indicated with star symbols. IRS 1, to the east, is the driving source of the large outflow. The square marks the position of the red outflow spectra shown in Fig. 4

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from their origin with an opening angle of $\sim 15°$. B97 find that the velocity structure is consistent with a steady flow with constant velocity (Cabrit et al. 1988). With this assumption the inclination of the outflow to the line-of-sight is determined to be 85°. The CO excitation temperature in the line core is greatest at the outflow peaks, indicating that the ambient gas there has been heated by interactions with the outflow.

Correcting for inclination, optical depth, and emission hidden within the line core, B97 determine the mass in the lobes to be $\sim 1.0 M_\odot$ (red lobe) and $\sim 0.3 M_\odot$ (blue lobe). Considering the different methods used to determine the outflow momentum P, kinetic energy E_k, and mechanical luminosity $L_{\rm mech}$ (upper and lower limit methods) B97 find $P = 11 M_\odot {\rm km\,s^{-1}}$, $E_k = 60 M_\odot {\rm km^2 s^{-2}}$, and $L_{\rm mech} = 0.5 L_\odot$. There is less mass in the blue lobe, which may be a result of this lobe breaking out of the globule, indicated in Fig. 1 by the conical reflection nebulosity just south of the protostars (see the beautiful colour VLT in the frontpiece of these proceedings for a more detailed view).

4 Two protostars - two outflows

Near-infrared (NIR) images from the AAT are shown in Figure 2 (Bourke 2001). Most of the non-stellar emission is due to the emission in the H_2 v=1-0S(1) line, most likely due to shocks in the outflowing gas (Eislöffel 1997). The NIR emission is well aligned with the large scale CO outflow (Fig. 3).

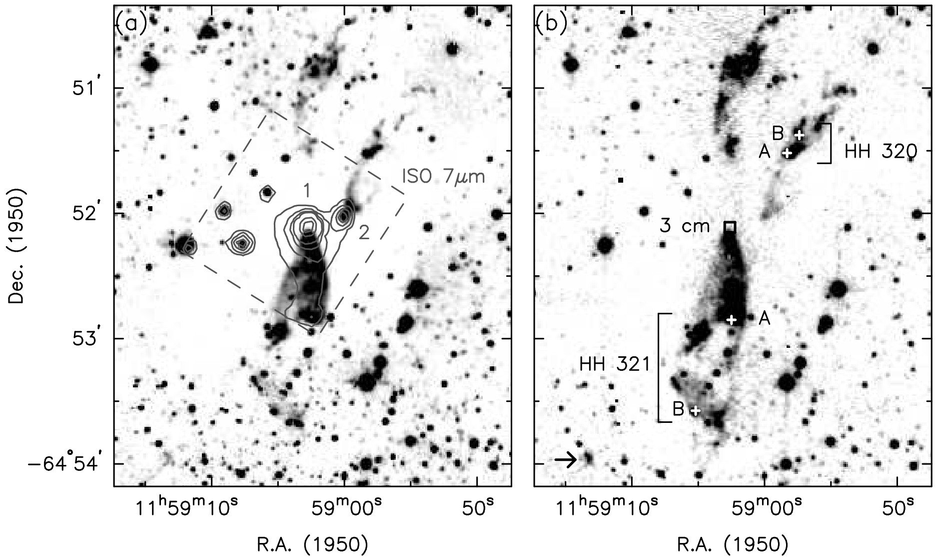

Fig. 2. (a) – K′ image of BHR 71 (greyscale) overlayed with ISO LW2 contours (5.0–8.5 μm). The embedded protostars IRS 1 ("1") and IRS 2 ("2") are labelled. (b) – Narrowband 2.12μm + continuum image (greyscale). The positions of HH 320 and HH 321 are marked with crosses, and the position of the 3 cm continuum source is marked with an unfilled box.

Mid-infrared (MIR) emission in the ISO LW2 band is overlayed on Fig. 2(a). Two of the 7μm sources appear to be located at the apexes of NIR emission, strongly suggesting that they are associated with the emission. Source "1" (hereafter IRS 1) lies at the apex of the reflection nebulosity seen also in Fig. 1 and is co-incident with the position of the mm source BHR 71-mm, also known as IRAS 11590-6452 (B97). The 7μm flux from IRS 1 is an order-of-magnitude greater than from IRS 2. The NIR feature coincident with IRS 2 in Fig. 2(a) is non-stellar, by comparison of its PSF with stars in the same image.

A cm continuum source (indicated on Fig. 2(b)) is detected toward BHR 71 IRS 1, at both 3 and 6 cm (Wilner et al. 2001, in prep). The spectral index is consistent with a flat or rising spectrum due to free-free emission, a signpost of protostellar origin (Rodríguez 1994). Corporon & Reipurth (1997) discovered two Herbig-Haro associations in BHR 71 – HH 320 and HH 321, and their locations are shown on Fig. 2(b). It can be seen that HH 320 (HH 321) is coincident with the NIR emission associated with IRS 2 (IRS 1).

Bourke (2001) has shown that IRS 2 also drives a CO outflow which is more compact and much less energetic than the IRS 1 outflow. The northern part of the IRS 2 outflow is blue-shifted (and associated with HH 320) which is the opposite of the IRS 1 outflow and allows them to be separated spatially. The red lobe is confused by the IRS 1 outflow, though it is probably seen in the NIR (arrowed emission in Fig. 2(b)). Bourke (2001) suggested that IRS 1 & 2 may form a binary protostellar pair (separation $\sim$3400AU) though the kinematic evidence for or against is lacking.

5 Outflow Chemistry

The BHR 71 IRS 1 outflow is one of a handful that show significant abundance enhancements in molecules such as SiO and CH_3OH (G98). Figure 3 shows the spatial distribution of SiO and CO in the outflow, compared to the NIR H_2 emission (the CO data is of lower spatial sampling than Fig. 1). Figure 4 shows spectra at two locations, the red lobe (as indicated by the box in Fig. 1) and at the position of IRS 1.

The spectral line profiles in the outflow and the velocity of the outflowing gas ($<$ 30km s^{-1}) indicate that C-shocks dominate the flow (G98). The shocks are sufficiently strong to release molecules and atoms into the gas phase via evaporation of icy grain mantles (e.g., CH_3OH) and sputtering of grain cores or grain-grain collisions (e.g., Si, which rapidly forms SiO). Other molecules detected in the outflow include CS, H_2CO, SO, HCN, HNC, HCO^+ with SEST and H_2O with SWAS (Bourke et al. 2001, in prep). SiO is removed from the gas phase in about 10^4 years indicating that the outflow is quite young.

In the red lobe G98 determined abundance enhancements of $\sim$350 in SiO and $\sim$40 in CH_3OH. One particularly striking feature is the spatial distribution of SiO compared to CO in the outflow. Because SiO is the result of Si liberation it is usually only detected at the ends of outflows (where the shock interaction is greatest) or as a narrow jet along the outflow axis possibly due to interactions in a turbulent boundary layer (Garay 2000). The wide-spread distribution of SiO in the BHR 71 outflow is unique. This suggests that the SiO enhancement takes place in a shell-like structure produced by the dynamical interaction between the ambient cloud and an underlying wide-angle wind or wind driven shell (Garay 2000), or perhaps by a wandering jet. However, it has not been shown that an interaction between a wind and the ambient material can produce sufficient Si for this to be a viable explanation. If sufficient Si-bearing species are present in grain mantles then the wind model becomes attractive (Schilke et al. 1997).

6 The VLT Image

An optical composite image taken with the VLT is shown in the frontpiece of these proceedings. This image hints at the spectacular results we can expect from the VLT in the coming years. There is evidence in this image of both a wind component and a jet component to the IRS 1 outflow in the blue lobe. Extending from the reflection nebulosity which protrudes from the globule, one can trace out an elongated bubble, with

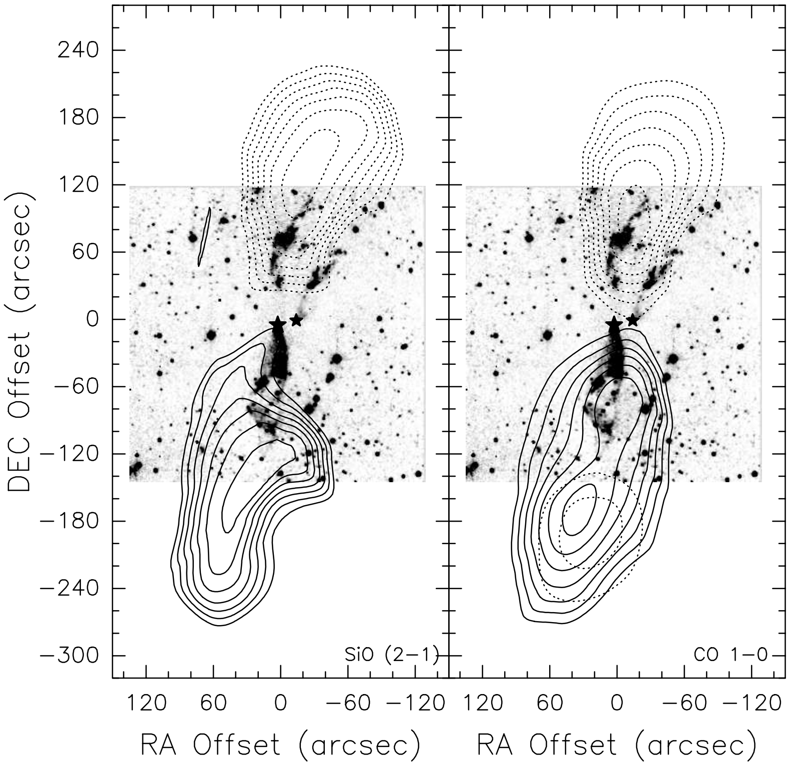

Fig. 3. SiO and CO integrated emission over the blue (solid lines) and red (dotted lines) lobes of the BHR 71 outflow, overlayed on the H_2 image from Fig. 2. The protostars IRS 1 (large star) and IRS 2 (small star) are indicated.

its edges defined by enhanced extinction. This is characteristic of a wide-angle wind component. In addition, enhanced extinction is also seen along the axis of the bubble and extending beyond its southern tip. This may be an indication of the underlying jet which is probably driving this young outflow. Modelling of this one image may help answer some of the remaining questions about the spectacular BHR 71 outflow.

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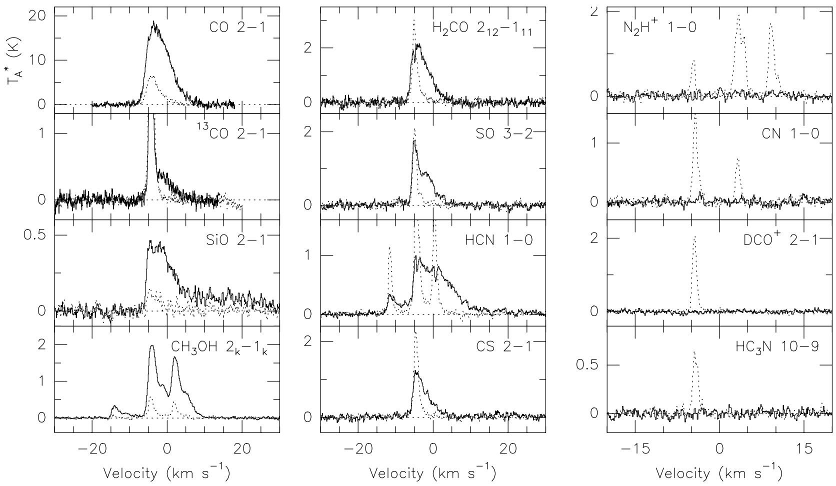

Fig. 4. Line profiles observed toward the red shifted lobe (continuous lines - indicated by the square on Fig. 1) and IRS 1 (dotted lines) of the BHR 71 outflow.

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