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CO and optical observations of the Magellanic Bridge*

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Abstract. We present ^{12}CO(1-0) molecular line and BV CCD observations towards 0311-7651, a region in the Magellanic Bridge where cold atomic Hydrogen has previously been detected by Kobulnicky & Dickey. Additionally, BV images of a comparison field 1° to the South were taken. No CO was detected to a limit of $\sim$ 0.06 Kelvin, and the colour-magnitude diagrams show no evidence for a stellar association in either field.

Key words: galaxies: ISM – galaxies: Magellanic Clouds – galaxies: photometry – radio lines: galaxies – radio lines: ISM

1. Introduction

Within galaxies such as the Milky Way and the Magellanic clouds, star formation is thought to occur within molecular clouds (Shu et al. 1987). The formation of these clouds is driven by many factors, including large-scale gravitational instabilities, shock waves from supernova explosions, random cloud-cloud coalescence and, within spirals, compression due to spiral density waves (Brosch et al. 1998). At some point after molecular cloud creation, a high density core is formed which collapses to form stars once it exceeds the Jeans mass (Vanhala & Cameron 1998).

Within environments where the gas density is lower, it is possible that collisions between H I cloudlets shock the gas and lead to star formation (Dyson & Hartquist 1983). One such region where this may be occurring is the region between the Large and Small Magellanic Clouds, the Magellanic Bridge. Even though the H I gas density in the bulk of the Bridge is relatively low (generally $\sim 10^{20-21}$ atoms cm^{-2}; McGee & Newton 1986), a number of blue stellar associations have still been formed within it (Irwin et al. 1990; Bica & Schmitt 1995). Spectroscopic analyses of individual stars in the Bridge yield stellar ages that are as young as 7 Myrs (Hambly et al. 1994). Such objects must have been formed within the intercloud medium, and not simply moved there from another birthplace.

In order to investigate the likely star formation mechanism within the Bridge, we have recently embarked upon a H I-line synthesis study, whose aim is to obtain the sizes, densities and velocities of Bridge gas cloudlets. The results will be compared to the predictions of Christodoulou et al. (1997) to see whether cloud-cloud collisions are a viable star formation mechanism within the Bridge. In parallel with the above work, the present study aims to search for molecular gas within the Bridge out of which stars may form. The recent detection of *cold* atomic hydrogen in the ICM by Kobulnicky & Dickey (1999, hereafter KD99) has fueled interest in this subject because within the Galaxy, cold H I is often associated with molecular clouds (Garwood & Dickey 1989). Similarly, within the LMC, Marx-Zimmer et al. (1998) found that 8/25 of pointings towards regions showing H I absorption also show CO in emission.

To our knowledge, no previous search for CO within the Bridge has been published. This is probably due to the perceived difficulty in observing any CO, caused by the ratio of molecular to atomic gas being much lower in the SMC and LMC than in the Milky Way (by factors of $\sim$ 15 and $\sim$ 4, respectively), combined with a conversion factor 'X' for I(CO)-H_2 which is some 20 and 6 times higher in the SMC and LMC than in the Galaxy (Israel et al. 1993 and references therein). As there is evidence that metallicities in the Bridge are even lower than in the SMC (Rolleston et al. 1999), and that fractional CO contents decrease with metallicity (Israel et al. 1993), CO studies in this region will inevitably be challenging.

The current paper describes a search for CO within the Bridge at one of the positions (0311-7651) where cold H I gas was detected by KD99. As the 0311-7651 region observed by KD99 lies just to the south of Bridge regions searched by Irwin et al. (1990) and Battinelli & Demers (1992), we have also undertaken a search for a stellar association towards this region using BV CCD photometry.

2. Observations and data reduction

2.1. Danish 1.54-m BV photometry

The BV CCD observations presented in this paper were obtained during three grey nights in December 1998 using the Danish 1.54-m telescope on La Silla. The LORAL/LESSER CCD was used, which has 2052^2 pixels giving a field-of-view

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[*] Based on observations made with the Danish 1.54-m and SEST telescopes at the European Southern Observatory, La Silla, Chile.

Table 1. Log of ^{12}CO(1-0) observations. DBS refers to the dual beam switch mode of operation when the beam throw is 11 arcmin. V$_c$ refers to the observed central velocity in the Local Standard of Rest. Coordinates are of equinox J2000.

Source RA hh mm ss	Source Dec ° ′ ″	Offset RA hh mm ss	Offset Dec ° ′ ″	V$_c$ (km s^{-1})	Time (min.)
03 11 54.8	–76 51 52	02 57 29.1	–76 57 02.8	200	150
″	″	03 21 41.6	–76 46 26.7	178	180
″	″	03 26 11.9	–76 43 17.8	200	150
″	″	03 02 05.9	–76 55 49.5	178	60
″	″	11′ DBS	11′ DBS	178	180

of ∼ 13.7′×13.7′. Two areas in the Bridge were observed; the region where H I absorption was detected by KD99 (0311-7651), and also a comparison field located 1° to the south (0311-7751). For each field a 2×2 grid was observed resulting in a fieldsize of ∼ 22′×22′, with an overlap of ∼ 4′ between adjacent grid positions. The integration time at each grid position was 300-s in B and V, with the seeing full width half maximum typically being ∼ 1.5″.

Data reduction was performed within the IRAF[1] environment. This included subtraction of dark current, debiasing and flatfielding (using twilight flats) to remove the pixel-to-pixel variations. Magnitudes for the programme stars were obtained by using point spread function fitting techniques within the DAOPHOT package. Observations of six standard stars (Landolt 1983, 1992) enabled the data to be corrected for the airmass and colour terms; the B and V data are thus tied to the Johnson system. Observations of the same standard stars on different nights indicate that on two of these (10 grid positions), conditions were photometric. For the remaining night (6 grid positions) where observing conditions were not photometric, the flux scale was bootstrapped using typically 10–20 stars in overlapping grid positions that were also observed on photometric nights.

The final magnitude list of stars is complete from $m_V \sim$ 15.0–22.0 mag. The bright end is limited by CCD saturation and the faint end by the signal-to-noise. Every V-band magnitude in this range has a corresponding detection in B. Occurrences where only a B or V magnitude was detected were frequently cosmic rays; these 'false positives' were removed from the final magnitude list if visual inspection showed them to be non-stellar. Similarly, extended objects such as galaxies were removed from the final magnitude list. It is noted that at the faint end there will remain some contamination by galaxies due to the difficulty in discerning these from stars at low signal-to-noise.

2.2. *SEST ^{12}CO(1-0) molecular line spectroscopy*

^{12}CO(1-0) observations (ν_0=115.271204 GHz) towards 0311-7651 were obtained using the Swedish-ESO submillimetre telescope (SEST) during 23-26 April 1999. The IRAM 115 GHz receiver was used in combination with the high and low resolution acousto-optical spectrometers (HRS, LRS respectively). For the HRS, the total bandwidth of 86 MHz was split into 2000 channels, resulting in a velocity coverage of ∼ 200 km s^{-1} and a resolution of ∼ 0.11 km s^{-1}. For the LRS, 1440 channels were contained within a total bandwidth of 995 MHz, giving a velocity resolution of ∼ 1.9 km s^{-1}. System temperatures lay in the range from 400–600 Kelvin. Every 2–4 hours, a pointing and focus test was performed using the SiO maser R Dor (RA=04^{h}36^{m}45.59^{s}, Dec=–62°04′37.8″, J2000). We had planned to observe three different regions in the Bridge, including the position of peak H I column density and another region observed by KD99, 0202-765. However, because observing time was lost due to high humidity and wind, we spent the full 12 hours of observing time towards 0311-7651.

As we expected *a priori* that any putative CO features would be faint, it was decided not to use frequency switching for the observations, for the reason that this *modus operandi* leaves noticeable baseline ripples in the final spectra, making identification of weak features difficult. Instead, we initially used position switching with the off-source position being located 40 and 60 arcmin away from the on-source field, positioned at points on a line joining the SMC to the LMC. This positioning was done in the hope that any CO in the off-source position would be shifted in velocity from that in the on-beam. At an assumed Bridge distance of 50 kpc, offset positions of 40 and 60 arcmin correspond to spatial distances of ∼ 580 and ∼ 870 pc respectively. Given that typical CO cloud sizes in the SMC are frequently smaller than a few arcmin (Rubio et al. 1996), it is likely, although not certain, that our adopted beam throws will not cancel out any CO detected in the on-source position.

For the final 3 hours of observing time, we used the dual beam switching mode of operation as the position-switched baselines were not as stable as we had hoped for. In this mode, the secondary mirror is nodded by 11 arcmin (or ∼ 160 pc) either side of the main source. Of course, using this mode increases the chance that CO in the reference beam position cancels out any CO in the on-source position. Finally, we note that ∼ 5 hours of observing were carried out with a central velocity of 200.0 km s^{-1} in the dynamical Local Standard of Rest (Allen 1973), with the remaining time at a velocity of 178.0 km s^{-1}. This shift was performed in order to more easily distinguish baseline ripples from real features. The observed source and position offsets are shown in Table 1.

The line data were analysed using the STARLINK SPECX package (Matthews & Jenness 1997). There were few interference spikes in the raw spectra although the quality of the baselines was variable. Data reduction simply consisted of combining spectra after weighting by their root mean square noise level and subtracting a low order polynomial from the co-added spectrum. The final spectra were converted to brightness temperature by dividing by 0.7 which corresponds to the main beam efficiency.

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[1] IRAF is distributed by the National Optical Astronomy Observatories, U.S.A.

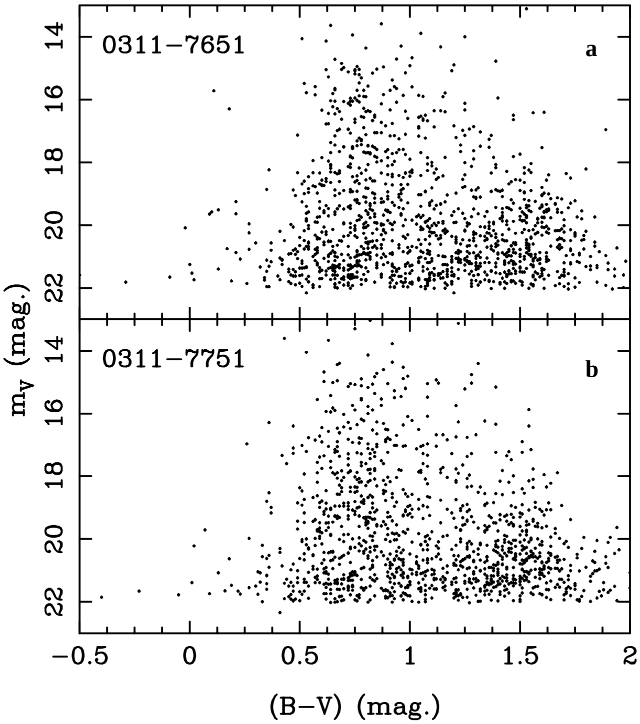

Fig. 1a and b. V vs. $(B–V)$ colour-magnitude diagram for **a** 0311-7651 and **b** the comparison field 0311-7751.

3. Results

3.1. *BV photometry*

Fig. 1 displays the V vs. $(B–V)$ colour-magnitude diagram for the two programme fields. No correction has been performed for Galactic reddening. Neither field shows a distinctive main sequence for Bridge stars as is observed in the main Bridge associations (Grondin et al. 1992; Demers & Battinelli 1998); if present this would be visible as a branch with $(B–V) \sim$ –0.2 to +0.2 mag. extending from $m_V \sim$ 16–22 mag. Fig. 2 shows the positions of stars with $m_V < 20$ mag. and $(B–V) < 0.5$ for both the source and offset fields. No obvious associations of blue stars are present in either field, although if any association were present it is likely to be sparse and difficult to identify. Finally, Fig. 3 shows a histogram of the V-band magnitudes for source and offset fields for stars with $(B–V) > 0.5$. Following Demers & Battinelli (1998), in Fig. 3 we also plot the predicted Milky Way field star counts in our observed area of $\sim 22\times22$ arcmin. These were calculated by averaging the counts in the direction of the SMC and LMC estimated by Ratnatunga & Bahcall (1985) over stars of all colours. Brighter than $m_V \sim 18$ mag., the predicted Galactic counts match the observed counts in source and offset fields. Fainter than this, there is an excess of objects in both fields. A substantial fraction of this population may be explained as being extragalactic (i.e. distant galaxies) in origin as such objects exceed the halo star population at $m_R \sim 19$ (Reid et al. 1996). At m_B=20, the predicted extragalactic count over an area of 22×22 arcmin is ~ 22. Of course, some of the excess may be due to bridge stars.

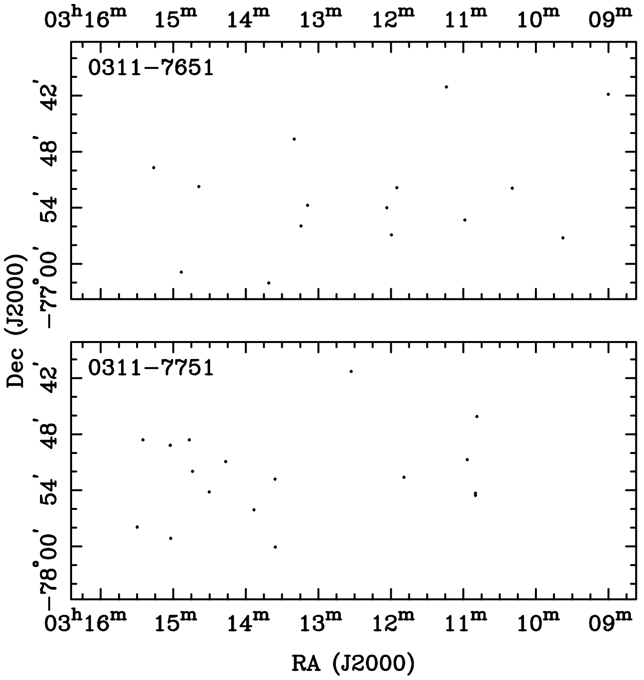

Fig. 2. Plot of sample stars in source and offset fields that have $(B–V) < 0.5$ and $m_V < 20$ mag.

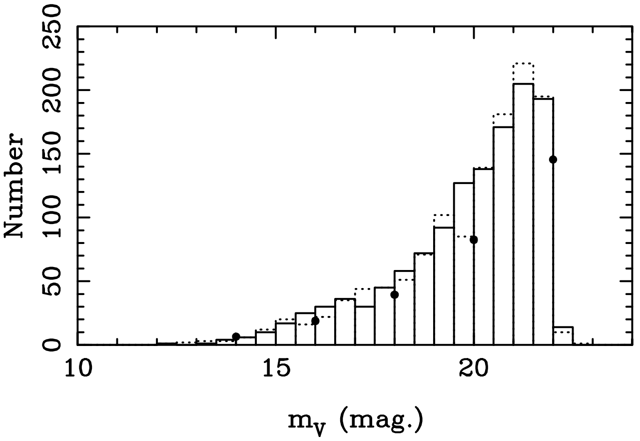

Fig. 3. Histograms of stellar V magnitudes towards 0311-7651 (filled line) and 0311-7751 (dotted line) with $(B–V) > 0.5$. Filled circles are the estimated Galactic halo contribution in the observed area of $\sim 22\times22$ arcmin.

3.2. *SEST molecular line spectroscopy*

Fig. 4a shows the final co-added spectrum for the position-switched data, with Fig. 4b showing the corresponding plot for the dual beam switched data. Spectra have been smoothed to a resolution of 1.1 km s^{-1}. The RMS noise values in the spectra are $\sim$ 0.015 K. Although there is a hint of emission at $\sim$ 170 km s^{-1} in Fig. 4a, this feature is probably due to baseline ripple rather than the presence of ^{12}CO. We thus conservatively place our detection limits at 0.08 K and 0.06 K for the position-switched and DBS spectra respectively.

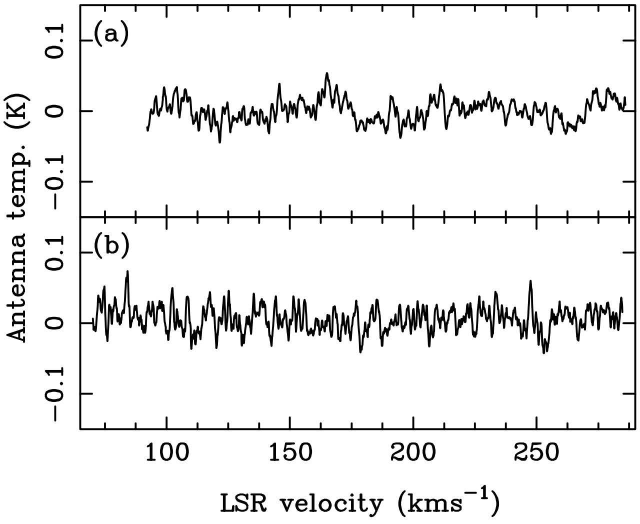

Fig. 4a and b. ^{12}CO(1-0) $SEST$ co-added spectra of 0311-7651 taken with the HRS and smoothed to a resolution of 1.1 km s^{-1}. **a** Spectrum taken with position switching by 40 and 60 arcmin. **b** Dual beam switched spectrum.

4. Discussion and conclusions

With regard to the optical results, the present images show no strong evidence for a stellar association in either source or offset field. This is unsurprising as the observed region lies at the extreme southern edge of the Bridge. It is possible, however, that a few of the bluer objects observed in Fig. 1 with m_V=19–22 mag. are stars associated with the young general field population of the Bridge (Demers & Battinelli 1998). Alternatively, such objects have the correct visual magnitude for blue horizontal branch stars at the distance of the Bridge. However, given the relatively young age of the Bridge (less than 200 Myr; Fujimoto & Murai 1984), combined with the fact that our observed position lies outside the haloes of both the SMC and LMC (Irwin et al. 1990) we believe this to be unlikely. A final alternative is that the blue stars may be foreground Galactic evolved blue horizontal branch stars. To distinguish between these various possibilities would require optical spectroscopy in order to determine stellar spectral types/luminosity classes and radial velocities.

Although disappointing, the lack of ^{12}CO detection is perhaps not surprising. Towards 0311-7651, and only considering Bridge velocities from 100–350 km s^{-1}, KD99 determined an H I column density of 1.2×10^{20} cm^{-2}, a peak temperature of 1.37 K and a brightness temperature integral of 65 K km s^{-1}. For the current data, assuming a SMC-like conversion factor from CO-H_2 of 6×10^{21} cm^{-2} (K km s^{-1})$^{-1}$, the limiting H_2 detectable column density is $\sim 3.6\times10^{20}$ ΔV, where ΔV is the width of the molecular line in km s^{-1}, which is typically 5 km s^{-1} for clouds within the SMC (Israel et al. 1993). Hence, for there to have been a detection at the current position, the H_2/H I ratio would have to have exceeded $3\times\Delta$V. Given that the H_2/H I ratio in the SMC is of the order 0.07 (Rubio et al. 1991), and assuming a similar ratio for the Bridge, it is clear that the current observations were of insufficient sensitivity to test this limit.

Future work in this area should concentrate on CO observations towards regions of higher H I column density within the Bridge. KD99 only sampled a few ICM regions for cold H I, and it may be that hydrogen in this phase, with associated CO, is present and detectable in other regions of the Bridge.

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