An excess of emission in the dark cloud LDN 1111 with the Arcminute Microkelvin Imager

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ABSTRACT
We present observations of the Lynds’ dark nebula LDN 1111 made at microwave frequencies between 14.6 and 17.2 GHz with the Arcminute Microkelvin Imager. We find emission in this frequency band in excess of a thermal free–free spectrum extrapolated from data at 1.4 GHz with matched uv coverage. This excess is $>15\sigma$ above the predicted emission. We fit the measured spectrum using the spinning dust model of Draine & Lazarian and find the best-fitting model parameters agree well with those derived from the Scuba data for this object by Visser, Richer & Chandler.

Key words: radiation mechanisms: general – stars: formation – ISM: dust, extinction – ISM: general – radio continuum: ISM.

1 INTRODUCTION
Recent pointed observations (Finkbeiner et al. 2002; Finkbeiner, Langston & Minter 2004; Casassus et al. 2004; Watson et al. 2005; Casassus et al. 2006; Dickinson et al. 2007; Scaife et al. 2007) have provided some evidence for the anomalous microwave emission commonly ascribed to spinning dust (Draine & Lazarian 1998a,b). Although this emission was originally seen as a large-scale phenomenon in cosmic microwave background (CMB) observations (see e.g. Kogut et al. 1996a,b), it has been suggested that the emission occurs in a number of distinct astronomical objects, such as dark clouds, and H ii and photodissociation regions. It often appears to be correlated with thermal dust emission as supported by the pointed observations mentioned previously, but it must be stated that this is not always the case (see e.g. Casassus et al. 2008).

In spite of these predictions, the evidence for anomalous microwave emission in compact objects is often contradictory. Early observations below 10 GHz of the molecular cloud LPH96 (Finkbeiner et al. 2002), which showed a rising spectrum, were later contradicted by observations at 31 and 33 GHz which found the emission consistent with an optically thin free–free spectrum extrapolated from lower frequencies (Dickinson et al. 2006; Scaife et al. 2007). Although some evidence for an excess was found in a sample of Southern H ii regions (Dickinson et al. 2007) and more significantly in RCW175 (Dickinson et al. 2009), no emission inconsistent with free–free was found in a sample of Northern H ii regions (Scaife et al. 2008). Casassus et al. (2004) proposed a flux density of approximately 1 Jy from the Helix planetary nebula at 31 GHz to be in excess of a free–free spectrum extrapolated from lower frequencies. However, based on flux densities from the literature at 1.4, 2.7, 6.63 GHz (Ehman, Dixon & Kraus 1970; Higgs 1971; Wall, Wright & Bolton 1976) and the recent Wilkinson Microwave Anisotropy Probe (WMAP) 5-year densities at 23–94 GHz (Wright et al. 2008), which are all also $\approx1$ Jy, we suggest that there is no evidence for this reported excess in the flux density spectrum, although the nebula may be anomalous in other ways.

In this Letter, we present observations of the Lynds’ dark nebula LDN 1111, taken from the Arcminute Microkelvin Imager (AMI) sample of compact Galactic star formation regions (Scaife et al., in preparation). This sample was selected from the Submillimetre Common-User Bolometer Array (SCUBA) sample of compact Lynds’ clouds (Visser et al. 2001).

The spectra of dark clouds at gigahertz frequencies are poorly documented in all but a few cases (Finkbeiner et al. 2004; Casassus et al. 2006, 2008). In those cases where cm-wave data are available (Casassus et al. 2006, 2008), the behaviour of these objects has been found to be anomalous in a number of ways and in the case of LDN 1622 (Casassus et al. 2006) to show a distinct excess of microwave emission.

LDN 1111 ($\alpha = 21^h40^m30^s$, $\delta = +57^\circ48'00''$J2000) lies on the inside edge of the heel of the large ($\approx 3'$) horseshoe-shaped H ii region IC 1396 (Sh 2-131; Sharpless 1959). It has no known IRAS association (Parker 1988) but has been studied in the submillimetre at 850 $\mu$m with the SCUBA instrument (Visser et al. 2001). An opacity class 6 object ($A_v \geq 5$ mag; Lynds 1962), it is one of the most opaque dark nebulae.
2 OBSERVATIONS

2.1 Calibration and data reduction

The AMI small array (SA) is a radio interferometer which observes in eight frequency channels in the band 12–18 GHz at the Mullard Radio Astronomy Observatory, Lord’s Bridge, Cambridge, UK. In practice, the lowest two frequency channels are generally unused due to a low response in this frequency range, and interference from geostationary satellites. AMI Consortium: Zwart et al. (2008) discuss the telescope in more detail.

Observations of LDN 1111 were made in 13 h over two days in 2007 November. The data reduction was performed using the local software tool REDUCE. This applies both automatic and manual flags for interference and shadowing and hardware errors. It also applies phase and amplitude calibrations; it then Fourier transforms the correlator data to synthesize the frequency channels before output to disk in FITS format suitable for imaging in AIPS.

Flux calibration was performed using short observations of 3C286 near the beginning and end of each run. We assumed I+Q flux densities for this source in the AMI SA channels consistent with Baars et al. (1977) \( \approx 3.3 \text{ Jy at } 16 \text{ GHz} \). As Baars et al. (1977) measure I and AMI SA measures I+Q, these flux densities include corrections for the polarization of the source derived by interpolating from Very Large Array (VLA) 5, 8 and 22 GHz observations. A correction is also made for the changing intervening air mass over the observation. From other measurements, we find that the flux calibration is accurate to better than 5 per cent (Scaefer et al. 2008; Hurley-Walker et al., in press).

The phase was calibrated using hourly interleaved observations of the point source J2201+508 (\( \alpha = 22^h01^m43^s5, \delta = 50^\circ48'56"4 \)), which has a flux density of 0.3 Jy at 16 GHz. It was selected from the Jodrell Bank VLA Survey (JVAS; Patnaik et al. 1992). After calibration, the phase is generally stable to 5\( ^\circ \) for Channels 4–7 and 10\( ^\circ \) for Channels 3 and 8. In this work, we use only Channels 4–7 due to their superior phase stability.

The full width at half-maximum (FWHM) of the primary beam of the AMI SA is \( \approx 20 \text{ arcmin at } 16 \text{ GHz} \). The FWHM of the synthesized beam of the combined channel map towards LDN 1111 is \( 2.4 \times 2.1 \text{ arcmin}^2 \) using natural weighting.

2.2 Imaging

The reduced visibilities were imaged using the AIPS data package. Dirty images were deconvolved using IMAGR which applies a differential primary beam correction to the CLEAN components to account for the different frequency channels of the AMI instrument. Maps were made from both the combined channel set, shown here, and individual channels.

Two objects are labelled in both Figs 1 and 2: object A, which is the dark cloud and object B, which is the NVSS radio source J213955+574859.

2.3 Radio spectra

Since the frequency coverage of AMI tells us nothing about the spectral behaviour at longer radio wavelengths, we must combine our new data with the existing archival data. Ideally total power measurements are required, with the same or better angular resolution than AMI. Data of this type allow sampling in the \( \mu \) plane to match exactly the measured angular scales of AMI. Here, we use data from the Canadian Galactic Plane Survey (CGPS; Taylor et al. 2003) at 1.42 GHz. These data are a combination of single-dish and synthesis data, and provide a total power measurement of this region with a resolution of \( \approx 1 \text{ arcmin} \). In order to mimic an AMI observation, these data are modulated by the primary beam of AMI before sampling in the \( \mu \) plane to match the AMI \( \mu \nu \) coverage. These data are then processed in the same way as the AMI visibilities to give the final sampled image. Fig. 2 shows the sampled data which result from matching the visibility coverage to AMI Channel 4.

Spectra of both LDN 1111 and the radio source J213955+574859 are presented, identified as objects A and B, respectively, in Fig. 1. Errors on the data points in these spectra are calculated using a contribution for the rms noise in each channel, a conservative 5 per cent flux calibration error and a contribution for the uncertainty in flux extraction. The morphology of LDN 1111 and its surroundings makes this extraction subject to the fitting area used. To account for this in the errors, 10 independent ‘fits’ are made. The recorded flux density is the mean of these measurements and the variance is referred to as \( \sigma^2_{\text{fit}} \). These errors are combined in quadrature: \( \sigma^2 = \sigma^2_{\text{rms}} + (0.05\, S^2 \sigma^2_{\text{fit}}) + \sigma^2_{\text{fit}} \). The flux extraction is performed using the FITFLUX program (Green 2007), which takes a
user-defined polygonal aperture and performs aperture photometry after subtracting a twisted plane background level. These errors are dominated by the 5 per cent calibration uncertainty, with the map rms being \( \approx 0.2 \text{ mJy per channel} \).

The spectrum of J213955+574859 is presented in order to demonstrate the flux calibration of AMI (see Fig. 3). The data points for this plot are given in Table 1. In addition to data points from the literature, flux densities at 408 MHz and 1.42 GHz from archival CGPS data are also plotted. These data have been extracted from the CGPS data are shown as unfilled triangles. Data points from the AMI are shown as filled circles.

Table 1. Flux densities for J213955+574859.

| Frequency (GHz) | Flux density (mJy) | Reference                      |
|----------------|-------------------|--------------------------------|
| 0.327          | 20.0 ± 4.8        | WENSS; Rengelink et al. (1997) |
| 0.408          | 13.4 ± 1.3        | This work; data from           |
| 1.420          | 12.2 ± 1.25       | This work; data from           |
| 1.420          | 11.1 ± 0.5        | NVSS; Condon et al. (1998)     |
| 14.631         | 3.48 ± 0.56       | This work                      |
| 15.381         | 2.88 ± 0.60       | This work                      |
| 16.130         | 3.02 ± 0.55       | This work                      |
| 17.150         | 2.93 ± 0.57       | This work                      |

Although an absolute measure of the flux loss is not feasible, it is possible to make an estimate of how the relative flux loss will affect the shape of the microwave spectrum. This is done using a multivariate Gaussian model for the source with dimensions of the deconvolved source at 14.63 GHz (AMI Channel 4) as given by the AIPS task IMFIT, \( 7 \times 4 \text{ arcmin}^2 \). This model is then sampled in \( uv \) using the exact coverage of the individual channels, and their flux loss relative to the lowest channel is recorded. We assume an uncertainty of 10 per cent on the percentage flux loss and propagate the errors. The results of this calculation are shown in Fig. 4 and are tabulated in Table 2. It should be noted that this is a conservative uncertainty and the relative flux loss will only be in error should the morphology change significantly between 14 and 17 GHz.

Fig. 4 includes a data point at 353 GHz (850 \( \mu \text{m} \)) from the Scuba instrument (Visser, Richer & Chandler 2001) for illustrative purposes. This data point is uncorrected for flux loss. These Scuba data at 850 \( \mu \text{m} \) are chopped at 2.5 arcmin, and consequently we would assume that information on scales larger than this is lost. To correctly estimate the flux loss at this frequency, we would require information on the morphology of the vibrational dust emission. Parker (1988), from whose paper the Scuba sample were selected, lists the dimensions of LDN 1111 as \( 1.7 \times 1.1 \text{ arcmin}^2 \). A multivariate Gaussian model based on these data would suggest a flux loss of approximately 73 per cent.

Table 2. Flux densities for LDN 1111.

| Frequency (GHz) | Flux density (mJy) | Relative flux loss (%) | Corrected flux density (mJy) |
|----------------|-------------------|------------------------|-----------------------------|
| 1.420          | 7.2 ± 0.7         | –                      | 7.2 ± 0.7                   |
| 14.631         | 50.7 ± 2.9        | –                      | 50.7 ± 2.9                  |
| 15.381         | 53.9 ± 3.2        | 10                     | 59.9 ± 6.8                  |
| 16.130         | 54.5 ± 3.3        | 17                     | 65.7 ± 7.6                  |
| 17.150         | 55.5 ± 3.3        | 24                     | 73.0 ± 8.4                  |

\( ^a \text{uv sampled CGPS data point.} \)
3 ANALYSIS

The emission seen between 14.63 and 17.15 GHz by AMI is clearly in excess of a simple free–free spectrum extrapolated from the CGPS data at 1.4 GHz. A number of possibilities may throw some light on the nature of this excess. The thermal (vibrational) dust spectrum of protoplanetary discs around T-Tauri stars is expected to extend into the cm regime. In these circumstances, grain growth has increased the population of cm-sized grains, or pebbles, causing β to approach zero and the greybody spectrum to fall off with an index approaching 2. However, the size of these discs is small and would be unlikely to be resolved by either AMI or Scuba. LDN 1111 is quite obviously elongated in the AMI data, as it is in the Scuba map which has a resolution of 14 arcsec. Although we do not deny the possibility of there being such a disc embedded within LDN 1111 or projected along the line of sight through this object, in the absence of further evidence we choose to pursue an alternative explanation.

A further possibility for a superposition of LDN 1111 and another object is that there may be an H II region, with a density such that it is still optically thick at 16 GHz, whose flux is contributing to the spectrum. An H II region with a turnover frequency >30 GHz, as would be required here, would possess an emission measure in excess of $4 \times 10^6$ pc cm$^{-6}$. This would put it in the regime of ultracompact and hypercompact H II regions. The spectrum of these objects is inverted with an index of $\sim -2$. The AMI data points alone have a spectral index of $\alpha = -2.86 \pm 0.35$, rather steeper than would be expected. Indeed, hypercompact H II regions exhibit slightly shallower spectra (Franco et al. 2000) which extend even to mm wavelengths. The lack of a visible source in the WMAP data towards LDN 1111 would suggest that this is not the case here. In addition, hypercompact H II regions tend to have very broad radio recombination line (RRL) widths, typically in excess of 50 km s$^{-1}$ (Kurtz 2005). Ultracompact H II regions also show broadened line widths of typically 30–40 km s$^{-1}$. The RRL measurement of Heiles, Reach & Koo (1996), which encompasses LDN 1111, has a width of only 21.4 km s$^{-1}$, although we note that this measurement is not specifically directed at LDN 1111. An emission measure of this magnitude would also imply an H II region mass of around 400 M$_\odot$ (Visser et al. 2001). The total mass of the cloud from the Scuba data (Visser et al. 2001) is 0.3 M$_\odot$ only, which given the calculated flux loss in these data implies an upper limit on the mass of 1 M$_\odot$.

A third possibility for the excess emission seen in the AMI data is that of the dipole emission from rapidly rotating small dust grains (Draine & Lazarian 1998a,b). The observational evidence for this emission mechanism has been explored in the introduction to this Letter. It is a relatively new emission mechanism and the evidence for its existence is not conclusive. We assess the possibility that the emission seen in LDN 1111 arises as a consequence of spinning dust by comparing the data to the model of Draine & Lazarian (1998a,b), which has been used extensively in the past. To make this comparison, we use the MCMC-based software METRO (Hobson & Baldwin 2004) to find the best-fitting parameters.

We fitted a model which has a free–free component normalized to the flux density at 1.4 GHz from the sampled CGPS data with a spectral index of $\alpha = 0.1$. To this, we add a spinning dust component scaled from the DL98 molecular cloud model.

The model is parametrized by the column density, $N(H_2)$, and the angular size of the object. Visser et al. (2001) calculate the average and peak column densities for LDN 1111 as 5 and $13 \times 10^{21}$ cm$^{-2}$, respectively. The results of our model fitting are $N(H_2) = 6.72 \pm 0.58 \times 10^{21}$ cm$^{-2}$ and $\Delta \theta = 5.38 \pm 0.26$ arcmin. These values provide a $\chi^2$ of 1.03 (79 per cent probability). However, given the small number of degrees of freedom in this case we do not propose this statistic as being conclusive. The resulting model is shown in Fig. 4. The column densities agree well with those of Visser et al., although as might be expected there is a degeneracy between the two parameters.

4 DISCUSSION AND CONCLUSIONS

Given the available evidence, we propose the excess of emission we see towards the dark cloud LDN 1111 in the microwave band to be a result of emission from small spinning dust grains. This excess is quantified relative to a flux density derived from lower frequency data sampled to give the same uv coverage and consequently measuring the same angular scales on the sky. Lacking further data at lower frequencies with suitable angular resolution, this one point is the basis for the assumption that there is an excess in the AMI frequency band. We therefore qualify this excess by using the original CGPS data to measure the total power, i.e. power on all scales, flux density at 1.42 GHz to be $S_{1.42,\text{total}} = 25.4 \pm 2.7$ mJy. Since the object is extended, this value may be regarded as an upper limit on the measurable flux at 1.42 GHz. In addition, the total power CGPS data at 408 MHz may then be used to better constrain the lower frequency spectrum: $S_{508,\text{total}} = 21.6 \pm 11.8$ mJy. The large error on this flux density is dominated by the fitting uncertainty. In combination, these two flux densities yield a spectral index of $\alpha = -0.16 \pm 0.12$, which predicts a total power flux at 16 GHz of $S_{16,\text{total}} = 36.9^{+17.8}_{-10.1}$ mJy. This suggests that even in terms of total power there is a clear excess at 16 GHz.

Relative to a canonical free–free spectrum extrapolated from our sampled CGPS data at 1.42 GHz, we see an excess of $S_{\text{excess}} = 60.1 \pm 7.6$ mJy, $\approx 8\sigma$, assuming a fixed spectral index of $\alpha = 0.1$. Using the spectral index derived from the CGPS, total power maps at 408 MHz and 1.42 GHz then there is an excess of $S'_{\text{excess}} = 55.10$ mJy, which is still $\ge 7\sigma$.

In conclusion, we have presented observations of the Lynds’ dark nebula LDN 1111 at frequencies of 14.6–17.2 GHz. These measurements show an excess of emission towards this object relative to an extrapolated free–free spectrum at a significance of $\approx 15\sigma$. We have proposed that this excess may be due to emission from small spinning dust grains and find that it is well described by the model of Draine & Lazarian (1998a,b).

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