Spectral Energy Distribution Reference Tables and Plots

R. E. Ainsworth, A. M. M. Scaife, D. A. Green, C. P. Coughlan and T. P. Ray,
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An extensive literature search was conducted for integrated flux densities (on scales comparable with the GMRT) to include in the spectral energy distributions following Ainsworth et al. (2012). Where uncertainties were not provided, an error of 10 per cent was used in the model fittings and this is indicated by a †. The reference list for the flux densities used in the L1551 IRS 5 spectral energy distribution (for $\nu < 1$ THz and in addition to the data presented in this work), can be found in the online supplementary material of Ainsworth et al. (2012) or `https://github.com/rainsworth/Spectral-Energy-Distributions/tree/master/2012MNRAS.423.1089A`.

The Markov Chain Monte Carlo based Maximum Likelihood algorithm METRO (Hobson & Baldwin, 2004) was used to fit a combined double power-law to the larger dataset of each source to model the two apparent emission components: free–free emission from the partially ionised outflow (with low frequency spectral index α) and thermal dust emission from the circumstellar disc/envelope (with high frequency spectral index α') using a joint likelihood. It is important to disentangle these two emission mechanisms simultaneously as it has been shown that considering free–free and thermal dust components separately can give vastly different values for the spectral slope and normalisation of each component (e.g. Scaife et al., 2012). This can have implications when determining physical parameters from the free–free spectra (such as gas mass and electron density) and the thermal dust spectra (such as disc mass and grain size).

In the Rayleigh–Jeans region ($h\nu \ll k_{\rm B}T_{\rm d}$, or $\nu \ll 1$ THz for a characteristic dust temperature $T_{\rm d} = 50$ K), the thermal emission from dust grains in the circumstellar environment can be well approximated by a power-law with $S_\nu \propto \nu^{\alpha'}$ (e.g. Scaife, 2013). The spectral index α' of flux density measurements is related to the dust opacity index β as $\beta \simeq (1+\Delta)\times(\alpha'-2)$, where Δ is the ratio of optically thick to optically thin emission (Beckwith et al., 1990). At long wavelengths $\Delta \rightarrow 0$ as the emission is entirely optically thin, so $\beta \approx \alpha' - 2$. This allows the largest grain sizes to be determined directly from a measure of this spectral index.

The fitted model is of the form,

$$\left(\frac{S_\nu}{\rm mJy}\right) = K_{323\,\rm MHz}\left(\frac{\nu}{323\,\rm MHz}\right)^{\alpha} + K_{100\,\rm GHz}\left(\frac{\nu}{100\,\rm GHz}\right)^{\alpha'}, \tag{1}$$

where the constants $K_{323\,\rm MHz}$ and $K_{100\,\rm GHz}$ normalise the two power-law components at 323 MHz and 100 GHz ($\lambda =$ 90 cm and 3 mm, respectively). Consequently, $K_{323\,\rm MHz}$ represents the normalised flux density at 323 MHz (expected to be dominated by free–free emission) and $K_{100\,\rm GHz}$ represents the normalised flux density at 100 GHz (expected to be dominated by thermal dust emission).

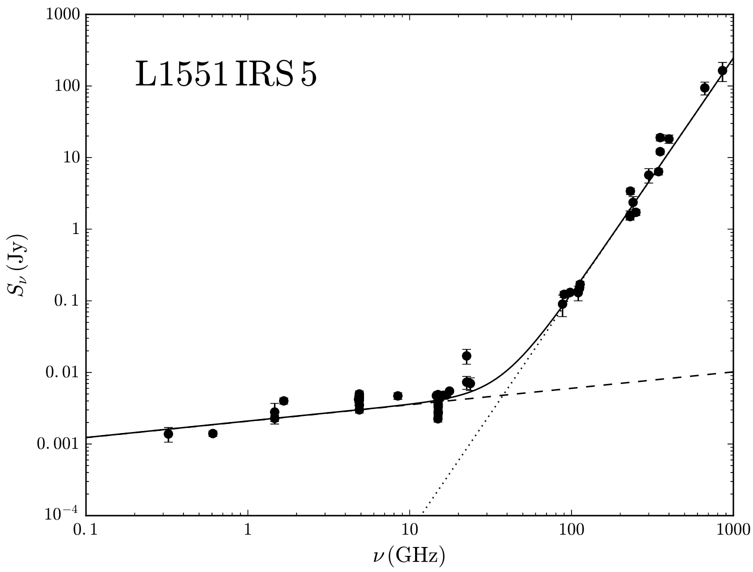
We fit all the available flux densities for each target source using uniform separable priors such that,

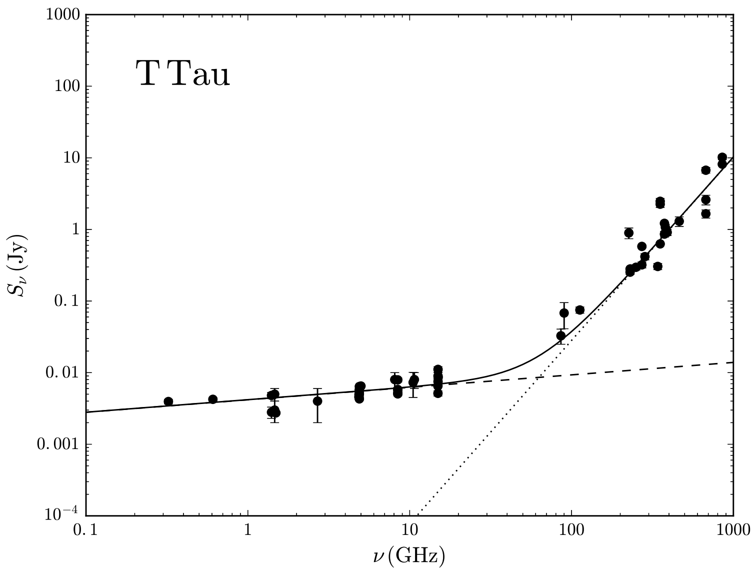
$$\Pi = \pi_{K_{323\,\rm MHz}}(0, 10\,{\rm mJy})\ \pi_{\alpha}(-2,2)\ \pi_{K_{100\,\rm GHz}}(0, 1\,{\rm Jy})\ \pi_{\alpha'}(0,4). \tag{2}$$

The prior range for α was selected to allow a variety of possible radio emission mechanisms such as synchrotron ($\alpha \lesssim -0.7$), optically thin free–free ($\alpha \approx -0.1$) and optically thick free–free ($\alpha \approx 2$). The prior range for α' was chosen to allow a range of values up to $\beta = 2$ expected for protostellar envelopes with small, warm dust grain populations (e.g. Scaife, 2013). The prior ranges for $K_{323\,\rm MHz}$ and $K_{100\,\rm GHz}$ were chosen based on the flux densities of these objects around 323 MHz and 100 GHz.

Table 1: SED modelling results. Column [1] contains the target source name; [2] the derived normalisation of the low frequency power-law at 323 MHz; [3] the derived low frequency spectral index α; [4] the derived normalisation of the high frequency power-law at 100 GHz; and [5] the derived opacity index β which is related to the high frequency spectral index α' as $\beta \approx \alpha' - 2$.

Source	$K_{323\,\rm MHz}$ (mJy)	α	$K_{100\,\rm GHz}$ (mJy)	β
L1551 IRS 5	1.61 ± 0.10	0.23 ± 0.02	120.58 ± 3.63	1.31 ± 0.05
T Tau	3.43 ± 0.08	0.17 ± 0.01	28.16 ± 1.15	0.56 ± 0.03
DG Tau	0.55 ± 0.05	0.20 ± 0.03	34.54 ± 1.08	0.55 ± 0.03


L1551 IRS 5
S_ν (Jy)
ν (GHz)


T Tau
S_ν (Jy)
ν (GHz)

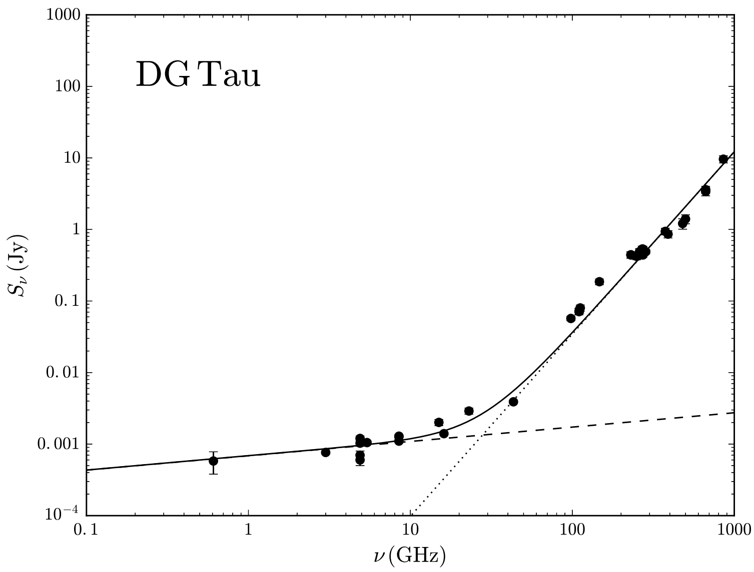

DG Tau
S_ν (Jy)
ν (GHz)

Table 2: T Tau

ν (GHz)	S_ν (mJy)			Reference
0.323	3.95	$\pm$	0.29	Ainsworth et al. (2016)
0.608	4.24	$\pm$	0.23	Ainsworth et al. (2016)
1.4	4.80		†	Condon et al. (1998)
1.4	2.80	$\pm$	0.50	Schwartz et al. (1986)
1.465	5.00	$\pm$	1.00	Rodríguez & Canto (1983)
1.465	3.00	$\pm$	1.00	Schwartz et al. (1984)
1.49	2.74	$\pm$	0.11	Cohen & Bieging (1986)
2.695	4.00	$\pm$	2.00	Spencer & Schwartz (1974)
4.86	4.94	$\pm$	0.34	Skinner & Brown (1994)
4.86	4.62	$\pm$	0.26	Skinner & Brown (1994)
4.86	4.53	$\pm$	0.29	Skinner & Brown (1994)
4.885	5.80	$\pm$	0.60	Cohen et al. (1982)
4.885	5.00	$\pm$	0.60	Rodríguez & Canto (1983)
4.885	4.30	$\pm$	0.20	Schwartz et al. (1984)
4.885	5.20	$\pm$	0.50	Bieging et al. (1984)
4.885	5.70	$\pm$	0.50	Schwartz et al. (1986)
4.885	6.40		†	Evans et al. (1987)
5	6.50	$\pm$	0.07	Cohen et al. (1982)
8.085	8.00	$\pm$	2.00	Spencer & Schwartz (1974)
8.44	5.19	$\pm$	0.30	Skinner & Brown (1994)
8.44	5.05	$\pm$	0.31	Skinner & Brown (1994)
8.44	5.79	$\pm$	0.34	Skinner & Brown (1994)
8.44	7.93	$\pm$	0.51	Skinner & Brown (1994)
8.44	5.81	$\pm$	0.41	Skinner & Brown (1994)
10.5	7.30	$\pm$	2.80	Maran et al. (1979)
10.69	8.00	$\pm$	2.00	Altenhoff et al. (1976)
14.94	6.50	$\pm$	0.07	Cohen & Bieging (1986)
14.949	5.14	$\pm$	0.43	Skinner & Brown (1994)
14.965	9.00	$\pm$	1.00	Schwartz et al. (1984)
14.965	7.50	$\pm$	0.70	Bieging et al. (1984)
14.965	11.10	$\pm$	1.00	Schwartz et al. (1986)
15	8.60	$\pm$	2.00	Bertout & Thum (1982)
86	32.7	$\pm$	7.8	Altenhoff et al. (1986)
90	68.0	$\pm$	27.0	Schwartz & Spencer (1977)
112.6	75.0	$\pm$	7.5	Weintraub et al. (1989b)
226	894	$\pm$	153	Altenhoff et al. (1986)
230	280	$\pm$	9	Beckwith et al. (1990)
230	253	$\pm$	18	Reipurth et al. (1993)
231	280	$\pm$	9	Andrews & Williams (2005)
250	296	$\pm$	25	Altenhoff et al. (1994)
272	320	$\pm$	30	Adams et al. (1990)
272	579	$\pm$	27	Weintraub et al. (1989a)
284	417	$\pm$	41	Beckwith & Sargent (1991)
341	304		†	Harris et al. (2012)
353	2250		†	Sadavoy et al. (2010)
353	2470		†	Di Francesco et al. (2008)
353	628	$\pm$	17	Andrews & Williams (2005)
375	1216	$\pm$	44	Weintraub et al. (1989a)
375	860	$\pm$	80	Jewitt (1994)
380	1070	$\pm$	110	Adams et al. (1990)
390	910	$\pm$	90	Beckwith & Sargent (1991)
463	1300	$\pm$	200	Adams et al. (1990)
676	2600	$\pm$	400	Adams et al. (1990)
676	1655	$\pm$	218	Andrews & Williams (2005)
676	6710	$\pm$	610	Weintraub et al. (1989a)
854	10170	$\pm$	730	Weintraub et al. (1989a)
854	8149	$\pm$	253	Andrews & Williams (2005)

Table 3: DG Tau

ν (GHz)	S_ν (mJy)			Reference
0.608	0.58	±	0.20	Ainsworth et al. (2016)
3.0	0.76	±	0.04	Ainsworth et al., in prep.
4.89	0.70	±	0.10	Cohen et al. (1982)
4.89	1.20	±	0.10	Bieging et al. (1984)
4.89	1.03	±	0.07	Cohen & Bieging (1986)
4.89	0.60	±	0.10	Evans et al. (1987)
5.4	1.05	±	0.05	Lynch et al. (2013)
8.5	1.27	±	0.05	Rodríguez et al. (2012)
8.5	1.29	±	0.07	Lynch et al. (2013)
8.5	1.10	±	0.06	Lynch et al. (2013)
15	2.01		†	Cohen & Bieging (1986)
16.12	1.40	±	0.07	Scaife et al. (2012)
23	2.90		†	Bertout & Thum (1982)
43.3	3.90	±	0.22	Lynch et al. (2013)
98	57.0	±	4.0	Ohashi et al. (1991)
110	71		†	Sargent & Beckwith (1989)
110	72		†	Kitamura et al. (1996a)
111	75		†	Sargent & Beckwith (1994)
112	80		†	Woody et al. (1989)
147	186	±	17	Kitamura et al. (1996b)
230	443		†	Beckwith et al. (1990)
230	440		†	Adams et al. (1990)
250	420	±	42	Altenhoff et al. (1994)
260	489		†	Beckwith & Sargent (1991)
270	532		†	Weintraub et al. (1989a)
273	440	±	30	Adams et al. (1990)
273	532	±	48	Weintraub et al. (1989a)
284	489	±	33	Beckwith & Sargent (1991)
375	940	±	100	Adams et al. (1990)
390	860	±	100	Beckwith & Sargent (1991)
480	1210	±	200	Beckwith & Sargent (1991)
500	1400	±	200	Adams et al. (1990)
666	3390	±	440	Weintraub et al. (1989a)
666	3600	±	400	Adams et al. (1990)
857	9600	±	1100	Adams et al. (1990)

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