The Spectral Energy Distribution of Galaxies
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Hot & cold dust in M31: the resolved SED of Andromeda

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Abstract. Due to its proximity, the Andromeda galaxy (M31, NGC 224) offers a unique insight into how the spectra of stars, dust, and gas combine to form the integrated Spectral Energy Distribution (SED) of galaxies. We introduce here *Herschel Space Observatory* PACS and SPIRE photometric observations of M31 which cover the far-infrared to sub-mm wavelengths (70-500 μm). These new observations reveal that the total IR luminosity of M31 is relatively weak, with $L_{\rm IR} = 10^{9.65} L_{\odot}$, only 10% of the total luminosity of M31. However, as seen in the previous studies of M31, the IR luminosity is dominated by a 10 kpc ring in all *Herschel* bands. This is distinct from the optical, where the bulge in the central 2kpc, dominates the luminosity, clearly demonstrating how different components at distinct positions in a galaxy contribute to make the integrated SED.

Keywords. Galaxies:individual:M31,ISM:dust

1. Introduction

The Andromeda galaxy (M31) has helped forge our understanding of the association of dust with gas and stars on galactic scales. The seminal work of Baade & Gaposchkin (1963) noted that in Andromeda the dust (as seen through extinction) was predominantly associated with young stars and hence star formation. Yet it was with far-infrared space telescopes that the dust revealed itself. The IRAS observations of M31 (Habing *et al.* 1984, Soifer *et al.* 1986, Walterbos & Schwering 1987, Xu & Helou 1996a,b) found the IR luminosity of M31 was relatively weak compared to many other galaxies found in the IRAS surveys. The IRAS survey found the IR maps dominated by the 10 kpc ring, as also found at 175 μm in the ISO survey of M31 (Haas *et al.* 1998).

The *Spitzer Space Telescope* view of M31 took this IR image to the next level of resolution, with the 10 kpc ring clearly visible in the IRAC 8 μm band (Barmby *et al.* 2006), and in the longer wavelength MIPS bands (Gordon *et al.* 2006). In addition to the larger 10 kpc ring, the MIPS imagery also revealed the central peak, and inner spirals and outer loops. Using this *Spitzer* data, in association with GALEX and SDSS imaging, Montalto *et al.* (2009) modelled the dust of M31, determining the dust mass distribution and importantly the heating of the dust across the disk. They found that over the majority of the disk the dust was heated predominantly by optical photons and stars older than 1 Gyr, as suggested in the earlier work by Xu & Helou (1996b).

In this paper we continue this investigation into the far-infrared properties of M31 with *Herschel Space Observatory* (Pilbratt *et al.* 2010) observations of the Andromeda galaxy. This data has given us an unprecedented look into the long wavelength emission from M31 and demonstrates that, overall, M31 has a low total IR luminosity and relatively low total dust mass. However, even with cold dust (long wavelengths), the 10kpc ring

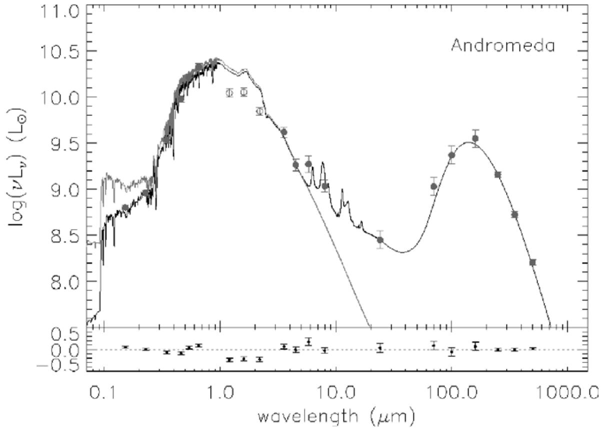

Figure 1. The spectral energy distribution of Andromeda (filled points), and the best fit model (black curve) from the SED fitting code MAGPHYS (da Cunha *et al.* 2008). Note that the 2MASS data (empty circles) were not used in determining the best fit due to the smaller aperture used. The solid curve shows the best model fit, while the grey line shows the unattenuated stellar spectrum. In the lower plot we show the offset of the data from the best fit model.

dominates the emission, but dust emission can be found out to radii even further than this. For full details of this work, we refer the reader to Groves *et al.* (in prep.).

2. The Integrated SED of Andromeda

The Andromeda galaxy was observed in all 6 *Herschel* photometric bands (PACS 70, 100, and 160 μm and SPIRE 250, 350, and 500 μm as a Guaranteed Time (GT1) program. A $\sim 3^\circ \times 1^\circ$ region centred on M31 was observed in slow parallel mode ($20''$/s) for a total time of $\sim$ 24 hours (86412 seconds). The full observations and reduction are described in detail in Krause *et al.* (in prep.).

Using literature data (UV from Gil de Paz *et al.* (2007), optical from Walterbos & Kennicutt (1987), near-IR from Jarrett *et al.* (2003), and the mid-IR from Barmby *et al.* (2006) and Gordon *et al.* (2006)) and the new *Herschel* data, it is now possible to obtain the full UV–IR integrated spectral energy distribution (SED) of the Andromeda galaxy, enabling a comparison of our nearest massive neighbour with more distant galaxies. We obtained the full SED of M31 within a $r_{\rm maj} \sim 95'$ ellipse, with an inclination of 75° and a P.A. of 37.7°, shown by the filled points in Figure 1.

Figure 1 also shows the best fit model SED from the SED fitting code MAGPHYS (da Cunha *et al.* 2008). Due to the significantly smaller aperture used to determine the 2MASS fluxes and the observable offset between these fluxes and the R and 3.6 μm bands, we have not included these in the determination of the best fit model. The offset between the best fit model and the observations can be seen in the lower part of Figure 1, including the offset of the 2MASS points.

It is immediately clear from the integrated SED that M31 is an early type spiral, with a relatively low UV and IR luminosity (c.f. the work of Mutch *et al.* 2011, who compare Andromeda with SDSS galaxies, and found that it fell in the "green valley"). The total luminosity of M31 from the best-fit model is $\log(L_*/L_\odot) \sim 10.61$. Only $\sim$10% of the radiation in M31 has been processed by dust, with $L_{\rm dust} = 4.44^{+0.15}_{-0.10} \times 10^9$ ($L_\odot$), and the subsequent radiation from the dust is predominantly cool, peaking at $\sim 160\mu$m. The total mass of dust returned by the model is $\log M_{\rm d} = 7.43 \pm 0.06 (M_\odot)$, supporting the idea that M31 is a dust poor galaxy. The mean cold dust temperature in M31 is $16.8^{+0.5}_{-0.7}$K,

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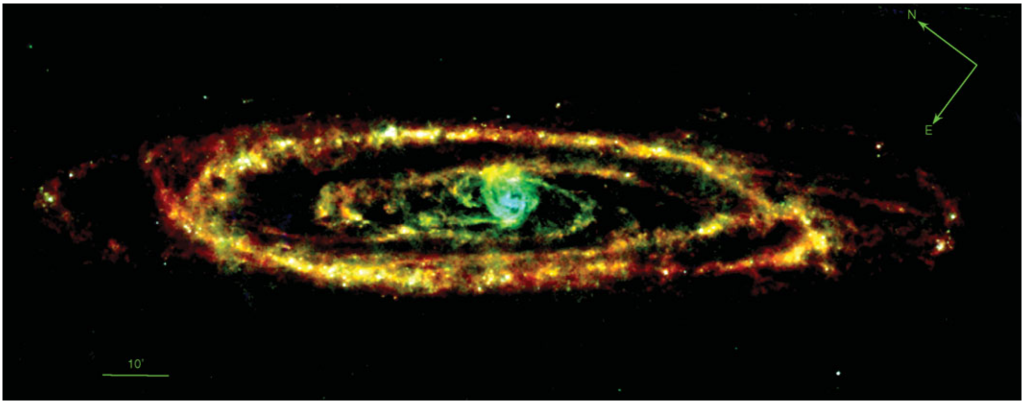

Figure 2. Far-infrared image of Andromeda using the Herschel bands showing PACS 70 μm, PACS 100 μm, and SPIRE 250 μm, all convolved to SPIRE 250 μm resolution. All three bands have the same square root scaling from 10 MJy/sr to 150 MJy/sr The angular scale is shown by the 10' bar in the lower right.

as expected with the peak of the IR bump at such long wavelengths. Altogether, M31 is a relatively dust-poor spiral with relatively cool dust, mostly because it is dominated by the emission from the diffuse ISM.

3. The resolved SED of Andromeda

The unprecedented spatial resolution of *Herschel* ($6-8''$, or 20–60pc at $70-250\mu$m), enables us to go further and determine the heating of the dust at the scales of HII regions and giant molecular clouds, and obtain the SED of Andromeda on small scales. In Figure 2 we show a three-colour far-infrared image of M31, using the PACS 70 and 100 μm and SPIRE 250 μm bands. All three bands have the same square root scaling from 15 MJy/ to 150 MJy/sr.

Clearly visible in the image is the 10 kpc starforming ring of M31 and its spiral structure, with bright white points indicating positions of HII regions. Outside the 10kpc ring, little dust emission is seen at these levels of surface brightness, except for the extended loops along the major axis. Inside the ring, the inner spiral arms are visible, linking the ring to both the nuclear and bulge emission at the centre. These features have been visible in both the earlier IRAS and *Spitzer* MIPS far-IR maps of M31, yet never before at such spatial resolution at these wavelengths. This image clearly demonstrates which regions contribute at which wavelengths, with the 10kpc ring dominating long wavelengths but the central region dominated by the shortest wavelengths.

This is more clear when we fit a simple modified blackbody, $F_\nu \propto B_\nu(\mathrm{T_d})(\frac{\nu}{\nu_0})^\beta$, to the 100–500 μm data. By minimizing over the other parameters, we determined the dust temperature T_d as a function of radius, shown in Figure 3. The radial variation quantitatively displays what was clear in Figure 2, with a high temperature in the central 2 kpc where the bulge of M31 is, while the disk of M31 has an approximately constant temperature ($T_\mathrm{d} \approx 17 \pm 1$K). This even includes the 10kpc ring, where little variation is seen with the mean T_d, though clearly there are individual hot HII regions within the ring. To the right of the radial temperature we show the integrated IR SEDs of the central 2 kpc (the bulge), and between 9 and 11 kpc (the ring) and the best fitting simple modified blackbody. While these two SEDs demonstrate the difference in dust temperatures between the two regions, they also reveal the relative contribution of these

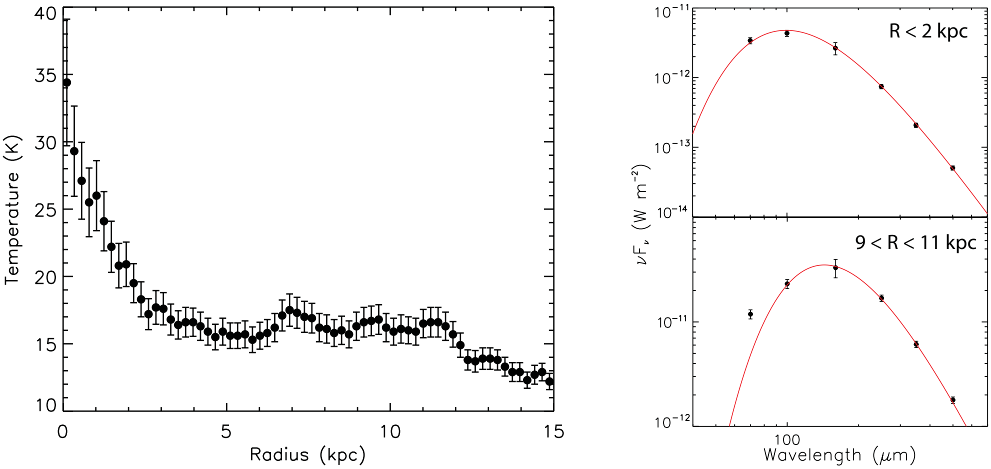

Figure 3. *Left*: Radial variation of mean temperature in M31. The temperature is determined by fitting the median flux in all bands in radial bins of 1′ (0.23kpc) width using elliptical annuli. The error bars show the 16-84 percentiles of marginalized PDFs. *Right*: The *Herschel* IR SED from the central 2kpc (*top*) and from the 10kpc ring (*bottom*) as labelled.

regions to each band, with the overall bulge IR emission an order of magnitude weaker than the ring, but having a relatively greater (though still weak) contribution at the shortest wavelengths.

As a final note, we point out that this work presents only a small fraction of the available information with these new *Herschel* images. With existing optical, GALEX, *Spitzer*, HI, radio, and CO data, and the currently ongoing Pan-chromatic Hubble Andromeda Treasury survey which will cover roughly a third of the star forming disk, using HST 6 filters from the UV–NIR, in addition to the *Herschel* images presented here, there exists a seemingly-overwhelming wealth of data on the Andromeda galaxy that should prove to be a heritage in understanding the connections between stars, gas, and dust and how they combine to make a galaxy.

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Discussion

Chakrabarti: Do you consider a range of temperatures? The reason I'm asking is that Chris McKee and I found that if you estimate masses assuming a single temperature, you would get a different answer than if you considered a self-consistent distribution of temperatures.

Groves: I agree. The simple models would not be able to give accurate masses. However, you can use simple modified blackbodies as a physically-motivated parameterization of the far IR colours. They are useful so long as you don't over-interpret the results.

Wang: Since M31 is highly inclined, do you see any evidence for projected dust features from the front side of galactic disk.

Groves: While most of the disk is optically thin we can see on the 3-colour Herschel image of M31 a portion where we have the disk dust emission projected onto the bulge.