Lecture 8: Studying galaxy evolution in the IR/sub-mm

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1 Introduction

In the previous lecture, we covered the use UV wavelengths to measure the star-forming properties of high redshift galaxies. We also looked at Lyman Break Galaxies, which are those galaxies that are *identified* exclusively via a *break* in their rest-frame continuum.[1]. However, as we've seen extensively already, the UV is heavily affected by absorption by interstellar dust, which needs to be accounted-for using uncertain correction factors. In this lecture, we'll consider the use of the longer infrared (1 μm − 500 μm) and sub-mm (500 μm − 1 mm) wavelengths to measure the star-forming properties of galaxies. These long wavelengths, especially $\gtrsim 30\ \mu m$, are almost impervious to absorption by dust.

2 What produces infrared emission in galaxies?

Infrared emission is produced by warm stuff. That's the case whether it's a (living) human body, coals on a fire, or a galaxy. In the latter case, the infrared is largely emitted by dust in the galaxy that is being heated by shorter wavelength, UV photons. These UV photons hit the dust particles, their energy goes into heating the dust particle, which then re-radiated the energy at infrared wavelengths. Eventually, this absorption of UV photons, heating and re-emission at infrared wavelengths reaches an equilibrium and the dust becomes a black body (i.e., with a continuum spectrum described by the Planck equation).

So, to emit in the infrared, a galaxy needs two things: dust, and a source of UV photons to heat the dust. It's still not entirely clear where dust comes from, but it's thought that supernovae (and thus star-formation) play a key role in dust production. There are two main sources of UV photons in a galaxy: the first and most common are hot, young stars, the second is emission from the accretion disk of an AGN. Typically, UV photons from populations of young stars will "heat" the dust to about 20-100 K (yes, it's still pretty cold, but much warmer than the $\sim$ 3K Cosmic Microwave Background). By contrast, AGN tend to produce more high energy UV photons, so are thought to heat the dust to warmer temperatures (although, as Clive will tell you, there is some contention on this issue).

[1]**Important note**: The presence of a breaks in galaxy continua is relied-upon heavily when measuring photometric redshifts. A break is a dramatic feature in the *shape* of an SED, so it helps a lot when "shifting" the synthetic spectrum in wavelength to find a photometric redshift

3 Early observations of the Universe at infrared wavelengths

Since most of the infrared part of the spectrum ($5 - 500$ μm) is absorbed by the Earth's atmosphere (largely by water molecules; the $1 - 5$ μm) wavelengths less-so), observations of the Universe at these wavelengths normally require space-based observatories. The first astronomically useful space-borne infrared telescope as **IRAS**, which was launched in 1983. This conducted the first infrared survey of the whole sky (at 12, 25, 60 and 100 μm). Remarkably, it remains the *only* all-sky survey at 60 and 100 μm).

During its lifetime, **IRAS** identified around infrared 350,000 sources. Many of these remain unclassified, but it is known that around 75,000 are extragalactic sources. Due to infrared astronomy being in its infancy when *IRAS* was launched, it suffered from poor sensitivity by today's standards. As such, it only detected the brightest infrared galaxies; all but the nearest ones are there extremely luminous at infrared wavelengths. Such galaxies are known as either *luminous infrared galaxies*, or LIRGs (with infrared luminosities $L_{\rm IR} = 10^{11} - 10^{12}$ ergs s^{-1}), and *ultra luminous infrared galaxies*, or ULIRGS $L_{\rm IR} = 10^{12} - 10^{13}$ ergs s^{-1}.[2].

On discovery of these bright infrared galaxies by IRAS, astronomers observed them in follow-up observations at optical wavelengths. What they found was that many of these infrared bright galaxies were in the process of undergoing *major mergers* of gas-rich galaxies.[3] In such cases, intense episodes of star-formation is triggered by the merger process compressing the gas within the merging galaxies, causing it to collapse to form stars at a very high rate. A LIRG is typically forming stars at a rate of 10-100 $M_\odot$ per year, whereas a ULIRG forms stars at a rate of 100-1000 $M_\odot$ per year. Because of their very high star formation rates, such galaxies are known as *starburst* galaxies.

Due to its low sensitivity, however, IRAS was not very good for exploring the high redshift Universe, so provided little insight into the evolution of galaxies at infrared wavelengths. Instead, this had to wait until the development of sub-mm astronomy in the mid-90's.

4 Sub-mm astronomy

As the name suggests, sub-mm astronomy exploits the wavelengths of light shortward of 1 mm, just before you enter the infrared regime at around 500 μm. It is the part of the spectrum between the radio and infrared. One of the greatest benefits of sub-mm astronomy over infrared astronomy is that the Earth's atmosphere is relatively transparent at these wavelengths, especially at very high altitudes at very dry sites.[4] As such, they are not as limited in terms of aperture size as infrared telescopes; indeed, the James Clarke Maxwell (JCMT) sub-mm telescope on Mauna Kea is 12 m in diameter. Despite its size, however, it still suffers from poor spatial resolution due to the long wavelengths it detects (remember, angular resolution$= 1.22\lambda/D$, where λ is wavelength and D is aperture size). For example, the angular resolution of JCMT is roughly 15 arcsec compared to $\sim$1 arcsec of ground-based optical telescopes.

[2]There are also HyperLIRGS, with $L_{\rm IR} > 10^{13}$ ergs s^{-1}, but these are extremely rare

[3]A major merger is usually defined as a galaxy merging with another galaxy with at least one third of the mass of the first. By contrast, a *minor merger* is usually defined as when a galaxy merges with another galaxy with a mass *less* than a third of the first.

[4]There are only a few places around the world that are high and dry enough to conduct sub-mm astronomy. Two of particular note are the summit of Mauna Kea on Hawai'i, and the Atacama Desert in Chile.

4.1 The positive K-correction of sub-mm observations

Another great benefit of sub-mm astronomy derives not from practical considerations, but the very shape of the infrared/sub-mm SED of galaxies. Recall from Lecture 2 the K-correction that needs to be applied to observations of high redshift galaxies due to the shifting of shorter wavelengths into the observed band. At optical wavelengths, this K-correction is said to be negative because it works against us: galaxies tend to be *less* luminous at shorter optical wavelengths, so when these fainter, shorter wavelengths are redshifted into our observing bands they are more difficult to detect. By contrast, at infrared and sub-mm wavelengths (longward of about 100 μm), galaxies tend to be *more* luminous at shorter wavelengths. As such, when these *brighter* shorter infrared wavelengths are shifted into our sub-mm observing bands, they are *more easily* detected. This *positive* K-correction almost exactly counteracts the $1/r^2$ cosmological dimming, meaning that a $z \sim 1$ galaxy is as easy to detect at 850 μm as a $z \sim 3, 4, 5$ galaxy! Not only that, but it can actually be *easier* to detect distant galaxies in the sub-mm than ones in the local Universe.

4.2 High redshift astronomy at sub-mm wavelengths

Because of the positive K-correction, sub-mm wavelengths are ideally suited to studying high redshift – and therefore distant, early – galaxies. However, early (1990s to the mid-2000s) sub-mm studies of high redshift galaxies were severely hampered by the poor resolution of the telescopes. When the sub-mm point spread function (PSF) is around 15 arcsec in diameter, it is extremely difficult to pinpoint which galaxy seen at optical wavelengths it corresponds to. For example, in the deep fields – where the first sub-mm surveys were conducted – Hubble could detect ten or more galaxies within a circle of diameter 15 arcsec. Which (if any) of those Hubble galaxies actually correspond to you sub-mm detection? Indeed, there could be more than one contributing to the total sub-mm flux of your sub-mm source. This causes significant problems for measuring the redshifts of your sub-mm galaxies. If you don't know which galaxy it is, you can't even use photometric redshifts, let alone target them for spectroscopic follow-up. It is possible, however, use the overall *shape* of the sub-mm SED to get a very crude redshift (often by just using a flux ratio to define the shape), but this only gives a redshift that's accurate to within $\Delta z \sim 1$, corresponding to roughly half the age of the Universe!

4.3 Using sub-mm wavelengths to measure SFRs

Under normal circumstances, the large uncertainties in the redshifts of sub-mm galaxies would scupper our chances of measuring the (rest-frame infrared) luminosities (see Lecture 4 for how we use infrared wavelengths to measure SFRs). And if we don't know their luminosities, we can't convert these into meaningful physical parameters such as star formation rates. Again, however, the positive K-correction saves us. Because the positive K-correction counteracts the $1/r^2$ geometric dimming, it means that a galaxy of a given luminosity *will have roughly the same sub-mm flux*, irrespective of its redshift (to within reasonable limits, and certainly to within $\Delta z \sim 1$). As such, as long as we have *some idea* of the redshift (from sub-mm flux ratios, for example) and a measured flux, we can convert it into a fairly confident infrared luminosity and, therefore, SFR (yep, it feels like cheating, but it actually works!).

With SFRs in hand, astronomers could work out the SFR density (i.e., the SFR per unit volume in the Universe) arising from sub-mm galaxies (SMGs) and plot this on the Madau plot (which we saw in L7). Although only based on a small number of sub-mm detected galaxies detected in the deep fields (remember, this was during the 1990's when sub-mm astronomy was still in its infancy) – and thus subjected to significant uncertainties – it appeared that SMGs were responsible for roughly the same contribution to the SFR density optical/UV-detected galaxies. Thus, sub-mm observations roughly doubled our estimates of the amount of star formation (per unit volume) taking place in the high redshift Universe.

Most importantly, sub-mm observations showed us that a significant proportion of star-formation activity in the Universe had been *completely missed* by optical/UV observations due to absorption by to dust. That's the equivalent of measuring global birth rates, then discovering India and China!

4.4 Pin-pointing the positions and redshifts of SMGs

As we have seen, during the mid-90's it became increasingly clear that SMGs were an important component of the star-forming history of the Universe. As a consequence, it became increasingly important that astronomers were able to pinpoint their positions more accurately, not least to obtain accurate redshifts.

Since all sub-mm galaxies are strongly star-forming, it was realised that observations at other wavelengths that are also sensitive to star-formation could also help to pinpoint them, provided they were higher resolution. However, as we've seen, we can't use the optical/UV, as it is blocked by dust. The (partial) solution came in the form of radio observations. This is because when stars undergo supernovae, they release a lot of radio emission due to synchrotron emission in the supernova ejecta. If a galaxy is strongly star-forming, it have a high rate of supernovae, and thus a strong radio luminosity. The benefit of radio wavelengths over UV/optical is that they are *completely impervious* to dust (if a radio wave can get through the walls of your house, it can easily penetrate interstellar dust). The other great benefit of radio wavelengths is that we can reach very high angular resolutions via radio interferometers (in fact, very long baseline radio interferometers provide the highest angular resolutions of *any* telescope).

By targeting sub-mm galaxies with radio interferometers, astronomers were able to pinpoint the positions of some of them to within about 1 arcsecond. This is easily accurate enough for follow-up optical spectroscopy, from which spectroscopic redshifts could be obtained. Unfortunately, not all sub-mm galaxies are detectable at radio wavelengths due to the relative sensitivities of our telescopes at different wavelengths (recall the biases introduced by multiwavelength surveys discussed in Lecture 6). Similarly, even if we have a radio position, that is no guarantee that our optical telescopes will be able to obtain a redshift since, by their nature, sub-mm galaxies are heavily obscured at optical wavelengths. As such, by 2005, only around 50% of the 150 brightest sub-mm galaxies had secure spectroscopic redshifts.

4.5 SMGs in context

Acknowledging the above problems, with the redshifts that we *did* have, it was clear that sub-mm galaxies were, indeed, more common at high redshifts. Their numbers peak at around redshift $z \sim 2.4$. With precise redshifts, we could finally obtain precise infrared luminosities and, thus SFRs, which revealed that sub-mm galaxies typically had SFRs over 100 $M_\odot$ per year. It was also confirmed that the SFRs of sub-mm galaxies are at least 100 times *higher* than what would be estimated via the rest-frame UV (when they are even detected at these short wavelengths and after trying to correct for dust obscuration), meaning that most of the star formation is hidden by vast columns of dust.

Sub-mm galaxies therefore have SFRs that are roughly similar to ULIRGs today. However, ULIRGs in the local Universe are extremely rare - roughly one per ten million Mpc^3. By contrast, sub-mm galaxies are roughly a thousand times more common at $z \sim 2.5$ than ULIRGs are today. This correxponds to a much higher SFR density, as seen when the contribution from sub-mm galaxies are included on the Madau plot.

It is interesting to compare SMGs against the other main type of star-forming galaxies at high redshift: Lyman break galaxies (LBGs). After correcting for dust extinction, LBGs and sub-mm galaxies contribute roughly equal amounts to the total SFR density of the Universe at $z \sim 2 - 2.5$. However, unlike LBGs, whose contribution continues to remain significant to higher redshifts ($z \sim 5$), the contribution from sub-mm galaxies drops away at higher redshifts. As such, the sub-mm "phase" of the Universe is, by comparison, fairly short lived, lasting from $z \sim 3$ to $z \sim 1$, or roughly 4 billion years.

Finally, since the density of SMGs peak at $z \sim 2.4$, and with today's most massive galaxies already in place by $z \sim 3$, it is unlikely that we are witnessing in SMGs the build-up of today's most massive galaxies. That role seems to be being played-out by LBGs at higher redshifts. Indeed, it's still not entirely clear what SMGs evolved to become in the current Universe.

5 Spitzer's contribution to infrared astronomy

As we have seen, for many years after IRAS completed its all-sky survey, infrared astronomy was dominated by observations at sub-mm wavelengths (and that's not a contradiction: sub-mm observations of high redshift galaxies samples the rest-frame infrared). This changed in 2003 with the launch of *Spitzer*, which was significantly more sensitive (by roughly a factor of 1000) at $3.6 - 160$ μm than any telescope that had gone before. Unlike IRAS, however, it did not perform an all-sky survey. However, it was the first infrared telescope to conduct blank-field surveys comparable in depth to those provided by Hubble in previous years.

Due to its excellent sensitivity at infrared wavelengths, Spitzer was capable of detecting tens of thousands of *high redshift* galaxies in the deep field, *despite* the negative K-correction.[5] Most of the sources that Spitzer detected in the deep fields were either LIRGs (at redshifts between 0.8 and 1.5) or ULIRGs (at $z > 1.5$).

The greatest benefit that Spitzer has over previous infrared/sub-mm observatories was, however, its angular resolution, allowing its tens of thousands of infrared-detected galaxies to be pinpointed to with a few arcseconds. This allowed the Spitzer-detected galaxies to be matched to galaxies detected at other wavelengths in the deep fields (recall, deep survey fields tend to be observed in many different wavelengths) which, correspondingly, enabled accurate photometric redshifts to be determined. For the first time, therefore, astronomers were able to determine accurate infrared luminosities – and thus SFRs – for *tens of thousands* of galaxies across large redshift ranges.

5.1 The evolving infrared luminosity function

With the availability of accurate luminosities and redshifts for many, many galaxies, astronomers used Spitzer to determine – for the first time – how the infrared luminosity function has evolved over the history of the Universe. This is a really important result: since the infrared traces star-

[5]It should be noted that, unlike sub-mm telescopes, Spitzer sampled the side of the dust's black body spectrum *shortward* of the peak and, as such, was subject to negative K-correction.

formation, what they were really plotting is how the histogram (recall, a luminosity function is just a histogram) of galaxy star formation rates have evolved over the history of the Universe.

In a result that echoed that of sub-mm observations, what astronomers found using Spitzer was that the number density (i.e., number per unit volume) of LIRGs and ULIRGs in the early Universe was *orders of magnitude* higher than in the current Universe. So, the peak in the Madau diagram wasn't caused by there being a higher density of galaxies of roughly the same SFR as today, but by today's galaxies growing much more quickly in the early Universe than they are today. It's as though most of today's galaxies went through a major growth spurt around 10 billion years ago.

5.2 Caveats with infrared astronomy

Hopefully by now you will have a sense of how important infrared and sub-mm astronomy is for our understanding of galaxy evolution. Before summarising this lecture, however, I would like to raise some caveats associated with infrared astronomy.

Firstly, recall all the problems associated with sub-mm observations. All these lead to significant selection biases that lead to large (systematic) uncertainties on our results. Despite Spitzer's high angular resolution solving some of these problems, it is still the case that many of the redshifts associated with infrared sources are photometric, rather than spectroscopic, and thus come with large uncertainties.

Secondly, throughout all of this Lecture, I've breezily mentioned that we can calculate infrared luminosities from observations sometimes at single infrared wavelengths (e.g., a single sub-mm or Spitzer band). However, implicit to this are a number of assumptions, in particular the shape of the SED and the conversion from infrared luminosity to SFRs. There is a whole host of poorly understood physics which determine the shape of the infrared SED and thus the conversion between a single band observation to an infrared luminosity. And there are less well-understood physics in converting infrared luminosities to star-formation rates. As such, there are a number of (often skipped-over) systematic uncertainties in measuring SFRs from infrared observations (although it's probably no worse than any other wavelength!).

6 Learning objectives for Lecture 8

In this lecture we covered the study of galaxy evolution at infrared and sub-mm wavelengths. Because these wavelengths probe the SFRs of galaxies, they provide a direct insight into how galaxies have grown over the history of the Universe. Here are the learning objectives:

- LBG, SMG and infrared-selected galaxies each contribute similar amounts of the global star formation density at z 2.
- For SMG and infrared-selected galaxies ¡10% of the star formation is directly visible at UV wavelengths.
- The SMG and infrared-selected galaxies together contribute $>$ 50% of the star formation density at high redshifts (based on the far-IR luminosities).