

Lifecycle of Dust in Galaxies

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The origin and evolution of galaxies is driven by the cyclical interaction between stars and the interstellar medium. On the one hand, stars are formed from interstellar material and the star formation process reflects the local ISM conditions. On the other hand, stars are key contributors of interstellar material when in the late stages of their life they inject most of their mass back into the ISM. As a result of this lifecycle, the ISM is slowly enriched in the nucleosynthetic products of the fiery cauldrons in stellar centers. Besides the mass budget, stars also dominate the radiative and kinetic energy budget of the ISM and thus the physical conditions of the gas which in turn determine the star formation rate. So, the evolution of galaxies is controlled by a complex feedback. Understanding the lifecycle of dust and the processes driving it is a key question in astrophysics.

Dust provides a convenient tracer of this cyclical interaction. In addition and equally important, dust is an active player in the evolution of the galaxies. The presence of dust in the ISM facilitates the formation of stars, strongly impacts the structure and ionization of the interstellar medium, and is an integral part of the mass (and metal) loss from stars. Recent observational advances have made it possible to begin studying the full cycle of dust from birth (in asymptotic giant branch stars, supernovae remnants, young stellar objects), through its life (in the interstellar medium), and to its death (in star formation regions) in our nearest neighbors, the Magellanic Clouds. Following the lifecycle of dust requires the ability to resolve individual stars, star forming regions, and interstellar clouds at ultraviolet, optical, infrared, submm, and radio throughout a galaxy. The combination of good spatial resolution and the ability to survey entire galaxies is crucial as this provides the necessary spatial resolution to resolve the crucial physics in each stage of the lifecycle of dust while also allowing the most basic unit of galaxy evolution to be studied, that is - an entire galaxy.

Magellanic Clouds

It is not surprising that the Magellanic Clouds are the first external galaxies where the full lifecycle of dust is being studied. They are nearby (50 & 60 kpc), large (50 & 25 sq.deg.), strongly star forming, and have different metallicities (1/2 and 1/5 solar). Recently, a large international group of astronomers have organized to study the lifecycle of dust in the Magellanic Clouds. This is the SAGE collaboration (Surveying the Agents of Galaxy Evolution) and is composed of a number of large projects including SAGE-LMC (Meixner et al. 2006), SAGE-Spec (Kemper et al. 2009, in prep.), and SAGE-SMC (Gordon et al. 2009, in prep.) Spitzer Legacies and the HERITAGE Herschel Key Project (PI: Meixner). In addition to these large Spitzer and Herschel projects, the SAGE collaboration includes surveys of both Clouds in the optical (MCPS), near-IR (2MASS, ISRF), HI, & CO. Unfortunately, a ultraviolet (UV) survey is missing as the Clouds are too bright for GALEX and this significantly limits the ability to study hot, young stars and the UV properties of dust. While the SAGE work is based on new infrared observations, it would not be possible without the existing surveys in the optical, near-infrared, and radio (HI & CO).

The SAGE collaboration is illuminating the lifecycle of dust in the Clouds by measuring the amount of dust that is forming in the atmospheres of evolved stars, that is currently existing in the

interstellar medium, and that is being consumed by star formation.

Dust Formation in Evolved Stars

The measurement of the amount of dust being injected in to the ISM can be done using mid-infrared measurements of the dust in the winds of evolved stars. The sensitivity of the SAGE-LMC/SAGE-SMC Spitzer observations is such that all stars with the significant mass-loss ($> 10^{-8} M_{\odot} \text{ yr}^{-1}$) are detected. For the LMC, the identification of the evolved star populations is presented in Blum et al. (2006) and has been further studied by Srinivasan et al. (2009, AJ, submitted). Srinivasan et al. studies the mass-loss from the two different types of oxygen-rich (O-rich) AGB stars, carbon-rich (C-rich) stars, and extreme AGB stars. An infrared excess is measured in these stars above the expected photospheric emission in these bands, as known from scaled model atmosphere profiles. The excess is due to the dusty, molecular rich mass loss experienced by AGB stars. Srinivasan et al. estimate a mass-loss rate for each candidate AGB star in the sample. The extreme AGB stars are the major contributors to the mass-loss rate, at $\sim 7 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$. The C-rich AGB stars and O-rich AGB stars contribute $\sim 1 \times 10^{-3}$ and $0.7 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$, respectively. The total mass-loss rate is $> 8.7 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$. This is a lower limit, as contributions from other sources (e.g., planetary nebulae, red supergiants, luminous blue variables, etc.) still need to be quantified and added to the total. This analysis is being extended to the SMC now that the SAGE-SMC observations have been completed. In addition, the measurement of dust mass loss rates from photometric excess measurements is being calibrated (and extended to determining the type of dust as well) using mid-IR spectroscopy from the SAGE-Spec program.

Dust in the ISM

The amount of dust in the present day ISM is most directly measured using far-infrared observations. The MIPS 70 & 160 μm imaging provides the most sensitive measures of the total dust mass in galaxies. Because the optical depth is quite low at these wavelengths, the emission is proportional to all of the dust mass and, by inference, the total gas in a galaxy independent of

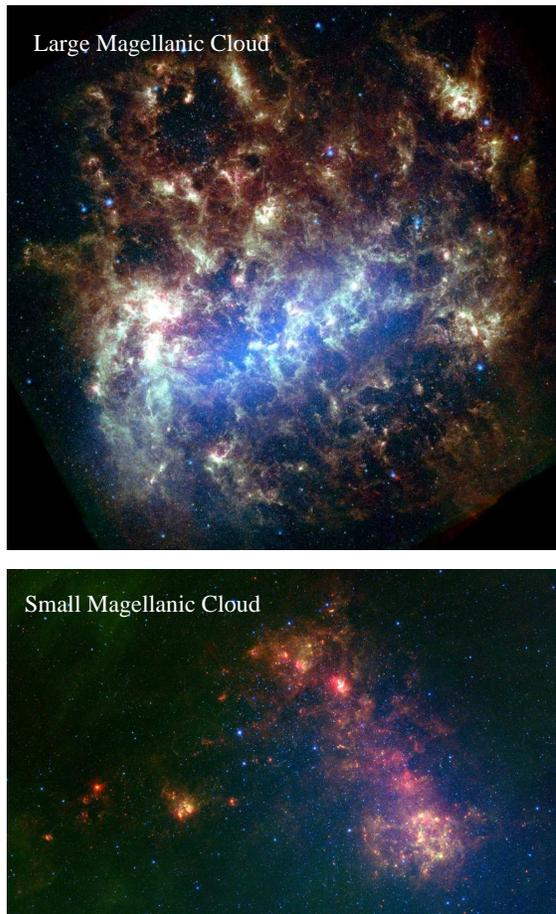


Fig. 1.— The Spitzer view of the LMC and SMC are as 3 color images where red=MIPS 24 μm , green=IRAC 8 μm , and blue=IRAC 3.6 μm . This 3 color image illustrates the stars (blue), ISM organics (green) and ISM/star formation (red).

the physical conditions (gas tracers are selective measures given their dependence on density). The SAGE observations are sensitive to dust columns of $0.2A_V$ and $0.4A_V$ (using appropriate gas-to-dust ratios, 1.2×10^{21} H cm² and 2.5×10^{21} H cm²) for the LMC and SMC, respectively, with a physical resolution of ~ 10 pc. For the LMC, the global view of the ISM dust properties derived from the SAGE-LMC data is presented by Bernard et al. (2008). Among the results is a derivation of the total mass of the ISM, which appears to be a factor of two larger than currently known from gas measurements of HI (Kim et al. 2003) and of CO (Fukui et al. 1999). The planned HERITAGE Herschel observations of both clouds will extend the study of the dust in the LMC and SMC to cooler temperatures. In particular, these observations will probe the presence of “very cold” dust ($T < 10K$) (Galliano et al. 2005) and, if detected, characterize its spatial distribution relative to the warmer ($T \sim 20K$) dust.

Dust Consumed in Star Formation

The measurement of the dust being consumed in the formation of new stars can be measured by studying young stellar objects (YSOs) and HII regions. The Spitzer SAGE surveys are sensitive to YSOs more massive than a few solar masses and, effectively, all of the HII regions. For the LMC, the view of star formation from YSO observations is presented by Whitney et al. (2008). The discovery of ~ 1000 new candidate YSOs, marks a major step forward in our understanding of the embedded star formation processes in the LMC. By fitting a Kroupa (2001) initial mass function to the portion of the mass distribution that was complete, Whitney et al. (2008) derived a star formation rate of $0.1 M_{\odot} \text{ yr}^{-1}$. This bottoms up approach to star formation rate provides a comparable value to that measured from the H α and far-infrared continuum emission. The HERITAGE Herschel observations will complete the census of the most embedded YSOs and enhance the characterization of already detected YSOs and HII regions.

Limits of Existing Data

Even with the current facilities our view of the Magellanic Clouds is limited in significant ways.

The most glaring hole in our view of the Clouds is the lack of sensitive surveys in the ultraviolet of the full Clouds. The Ultraviolet Imaging Telescope (UIT, Stecher et al. 1992) provided partial surveys of both Clouds (Parker et al. 1998), but GALEX is too sensitive for the necessary observations. This lack of UV observations limits the characterization of the hot star population and derivation of the spatial variations of the dust properties through the 2175 Å extinction bump and far-UV rise. Strong spatial variations of the UV dust properties is seen in both Clouds Gordon et al. (2003) and seems to be related to nearby massive star formation Gordon et al. (1997). Connecting the UV dust properties with the IR dust properties (mass and aromatic/PAH emission) is not possible without new UV data.

In the optical and near-IR, confusion due to the large number of sources limits the sensitivity of the ground-based surveys at these wavelengths. Higher spatial resolution is needed to reach the interesting parts of the CMDs and fully characterize the point source population. Such higher resolution observations have been taken for selected small regions using Hubble, but a full survey of the Clouds at this resolution is not possible due to its slow survey speed. In the far-infrared/submm

where Herschel will observe, the sensitivity is significantly limited by the relatively high temperature of the telescope. This means that for extended sources, Herschel is less sensitive to Spitzer in the overlapping wavelengths (70–160 μm) even though Herschel has over 4 times the collecting area.

More Distant Galaxies

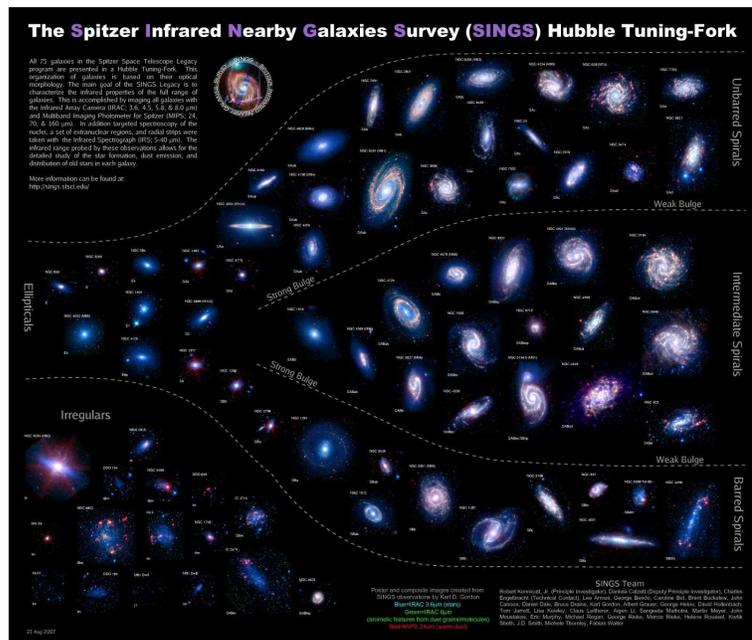
The SAGE work on the Magellanic Clouds is exciting and is providing major insights into the lifecycle of dust in galaxies, but the insights gained will be limited. The Magellanic Clouds represent only one type of galaxy, dwarf irregulars. Clearly, extending this kind of work to other galaxies in the Local Group and beyond will allow for the full range of galaxies (dwarfs, spirals, and ellipticals) to be studied.

The Spitzer Infrared Nearby Galaxies (SINGS) Survey (Kennicutt et al. 2003) is a good example of a sample which includes the full range of galaxies for which observations similar to those we now have for the Magellanic Clouds are needed to gain a general picture of the lifecycle of dust in galaxies. The SINGS observations with Spitzer and ground-based telescopes along with associated projects (e.g., THINGS) has allowed for a portion of the lifecycle of dust to be studied. This includes measurements of the global dust properties (Draine et al. 2007), studies of the aromatic/PAH features Smith et al. (2007), and

measurements of the HII region star formation rates (Calzetti et al. 2007). Due to the limited physical resolution in these distant galaxies, our view of the lifecycle of dust is much more limited than for the Magellanic Clouds. We don't have the ability to study the AGBs/YSOs and due to the much coarser physical resolution of 100–500 pc.

What is Needed

The promising results from the Magellanic Clouds on the lifecycle of dust demonstrate the need for similar work on more distant galaxies. The question arises: What capabilities are needed? Using the Magellanic Clouds as an example, the key capabilities are good physical resolution and the ability to efficiently survey large areas. Good sensitivity is also necessary, but this is a secondary desire as the observations of the Magellanic Clouds are usually done quite shallowly to ensure that the entire galaxies are covered. Mid- and far-Infrared observations are the most critical for this topic. For determining the mass loss from the evolved stars, it is necessary to include optical and near-infrared photometry. For interpreting the dust mass measurements, HI



and CO observations are needed and ultraviolet observations are greatly desired (UV extinction and scattering properties). Finally, to study star forming regions (YSOs and HII regions), ultraviolet, H α , and HI/CO observations are commonly added to the infrared observations. This illustrates the strong multi-wavelength nature of the study of the lifecycle of dust.

The natural next step in studying the lifecycle of dust in galaxies is to be able to study the galaxies in the Local Group. The Local Group includes a large spiral (M31), a dwarf spiral (M33), numerous star forming irregular galaxies and numerous dwarf spheriodals. While the Local Group does not include the full range of galaxies (e.g., SINGS sample), it does include examples of most of them. Studying the Local Group galaxies in this context is an excellent goal for the 2010-2020 decade.

We have listed the requirements needed to perform lifecycle of dust studies out to a distance of 1 Mpc using the existing studies/observations of the Magellanic Clouds as a guide. A common requirement is the ability to survey the largest galaxy in the Local Group in a reasonable amount of time. M31 is the largest galaxy at a size of $1^{\text{deg}} \times 5^{\text{deg}}$ (HI/IR size).

Evolved Stars

For the study of evolved stars, the requirement is to be able to survey the all of the important mass losing stars. This requires high enough spatial resolution that confusion due to crowding does not limit the sensitivity. In the Magellanic Clouds, the crowding is worst at IRAC wavelengths and IRAC has a angular resolution of $\sim 2''$. This translates to a physical resolution of 0.5 pc. Requiring the same physical resolution at a distance of 1 Mpc gives a requirement of an angular resolution of $0''.1$. Both imaging and spectra (5–45 μm) are needed to fully unlock the amount and type of dust mass loss from evolved stars. The mid-infrared capabilities of JWST are close to reaching this requirement (MIRI at 5 μm has a resolution of $0''.2$ and takes spectra from 5–28 μm). JWST should be able to efficiently measure the evolved stars in the key portions of the larger nearby galaxies and to entirely survey the smaller, more nearby galaxies in the Local Group. Ideally, a telescope that is similar to JWST (or 2x larger) with the ability to survey large areas is needed.

At near-infrared and optical wavelengths, the study of evolved stars will likely need somewhat higher spatial resolutions as the confusion due to crowding does become worse at shorter wavelengths. Thus, a survey telescope with spatial resolutions of, say, $0''.05$ would be needed at 1 μm and $0''.025$ or better at 0.5 μm . This translates to a telescope with a diameter of around 5 m at 1 μm and 2.5 m in the optical. Thus, JWST and HST (respectively) provide the necessary resolution, and targeted observations of key regions in large galaxies and entire galaxy surveys in small galaxies will be performed.

Interstellar Medium

For measuring the dust in the interstellar medium, the main need is for measurements that resolve clouds and cloud complexes in the far-infrared. The long-wavelength Spitzer (and Herschel) resolutions of ~ 10 pc is sufficient. For the Magellanic Clouds, this is a resolution of $\sim 40''$. At a distance of 1 Mpc, this is a resolution of $8''$. The peak wavelength of dust emission is in the 100–200 μm range and this is where the resolution would be needed. Herschel provides this resolution,

but cannot fulfill the necessary sensitivity requirement due to the relatively warm telescope (~ 80 K). A Herschel sized telescope (3.5 m) that is as cold as Spitzer (6 K) and can survey large areas (like Herschel and Spitzer) would be idea for ISM studies.

Other data that is crucial for a full characterization of the dust in the ISM is ultraviolet, far-infrared line emission (CII & OI), and radio (HI & CO). The ultraviolet is used to characterize the type of dust (scattered light) and the heating sources (hot stars). The spatial resolution of GALEX is sufficient for the dust scattering ($5''$), but it is likely not sufficient to deal with the confusion due to crowding of the hot stars. Something like $1''$ (2.5 m) would likely be sufficient, especially in the far-UV where hot stars are the dominant emitters. The two broad band filters on GALEX are not sufficient for characterizing the dust type and scattering. A minimum of 4 medium band filters placed to sample the 2175 \AA feature (3 bands) and the far-UV rise (1 band) are needed. The radio observations of HI and CO would need to have the same spatial resolution as the far-IR, something like 10 pc. For the CO observations, ALMA will be the instrument of choice in providing the necessary resolution. In order to understand the ISM phases in which the dust resides, we will need information on the main cooling lines of the ISM gas, such as CII and OI, which will be accessible by Herschel and SOFIA.

Star Formation

For star formation studies, the need is for mid-IR, far-IR, ultraviolet, optical, near-infrared, and H-alpha observations that resolve star formation regions and YSOs. The desired capabilities already listed for evolved stars and ISM studies above are sufficient for the mid-IR, far-IR, ultraviolet, optical, and near-IR observations. The H-alpha observations required are well covered by large optical cameras on existing telescopes. The fact that the same capabilities needed for life-cycle of dust studies of evolved stars and ISM also work for star formation studies illustrates the observational complementarity between the three parts of the lifecycle.

Summary

The next decade holds great promise for the study the life cycle of dust in nearby galaxies. It requires the synergy of multiple observatories operating at different wavelengths to make the necessary advances. Both existing facilities (JWST, HST, Herschel, SOFIA and ALMA) and new facilities are required. New facilities needed include a cooled ($T \sim 5$ K) space-based far-infrared observatory, ultraviolet/optical/near-infrared 2.5–5 m space-based observatory with high survey speed, and a space-based mid-infrared 5–10 m observatory with high survey speed.

REFERENCES

- Bernard, J.-P., et al. 2008, *AJ*, 136, 919
- Blum, R. D., et al. 2006, *AJ*, 132, 2034
- Calzetti, D., et al. 2007, *ApJ*, 666, 870
- Draine, B. T., et al. 2007, *ApJ*, 663, 866
- Fukui, Y., et al. 1999, *PASJ*, 51, 745
- Galliano, F., et al. 2005, *A&A*, 434, 867
- Gordon, K. D., Calzetti, D., & Witt, A. N. 1997, *ApJ*, 487, 625
- Gordon, K. D., et al. 2003, *ApJ*, 594, 279
- Kennicutt, Jr., R. C., et al. 2003, *PASP*, 115, 928
- Kim, S., et al. 2003, *ApJS*, 148, 473
- Kroupa, P. 2001, *MNRAS*, 322, 231
- Meixner, M., et al. 2006, *AJ*, 132, 2268
- Parker, J. W., et al. 1998, *AJ*, 116, 180
- Smith, J. D. T., et al. 2007, *ApJ*, 656, 770
- Stecher, T. P., et al. 1992, *ApJ*, 395, L1
- Whitney, B. A., et al. 2008, *AJ*, 136, 18