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OUR CURRENT UNDERSTANDING OF THE DUST PROPERTIES OF NEARBY GALAXIES

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Abstract. This article gives a brief overview of our contemporary knowledge of the dust properties in nearby galaxies. It puts these properties in perspective by comparing them to those of the Milky Way, our current best standard, and demonstrates how instrumental they are to understand the evolution of distant galaxies. I start by linking the microphysical processes to observations of macroscopic regions in external galaxies, presenting the information brought by measures of extinction, emission and depletion. I then discuss what the detailed knowledge of nearby galaxies brings to our comprehension of dust evolution and emphasize the importance of low-metallicity galaxies to understand the grain properties at early stages. I end this review by delineating a few prospective studies.

Keywords: ISM: dust, ISM: extinction, ISM: abundances, galaxies: evolution, galaxies: dwarf

1 Introduction

Interstellar dust is a key physical ingredient of galaxies, obscuring star formation, regulating the heating and cooling of the gas, and building-up chemical complexity (Draine 2003; Galliano et al. 2018, for reviews). Its ubiquity makes it a privileged diagnostic tool of the physical conditions in unresolved galaxies and obscured star forming regions. Its properties are however difficult to grasp because of the inherent intricacy of the grain make-up and its non-trivial evolution through the InterStellar Medium (ISM). We are currently far from being able to model *ab initio* the build-up and evolution of interstellar dust. The advances in this field therefore rely primarily on the information brought by observations of a large diversity of systems, throughout the whole electromagnetic spectrum, in order to constrain phenomenological models.

Nearby galaxies are important objects to unveil interstellar dust, as they harbor a wide range of physical conditions, allowing us to study dust in extreme conditions. At the same time, their proximity permits detailed, spatially-resolved studies, that are not yet possible in more distant systems. Fig. 1 illustrates this diversity of environments. Overall, there is a hierarchy in the way the knowledge in this field is acquired. Milky Way studies provide the richest observational constraints, allowing us to build detailed dust models (*e.g.* Jones et al. 2017). The Milky Way is however a particular environment and these models can not be straightforwardly applied to other systems. Nearby galaxies are the intermediate that allow us to understand the effects of metallicity*, star-formation activity and gas fraction on the grain properties. Nonetheless, nearby galaxies significantly differ from distant ones. The latter need dedicated studies despite the difficulty to observe them. If we survey the literature over several decades, we see that there is a parallel progress between these three classes of objects: we are now modeling in distant galaxies the well-constrained panchromatic Spectral Energy Distribution (SED) (*e.g.* Burgarella et al. 2020), which was only available in the nearby Universe, fifteen years ago; we are also performing spatially-resolved dust evolution analyses at the scale of molecular clouds in nearby galaxies (*e.g.* Galliano 2017), which was only available in the Milky Way, previously.

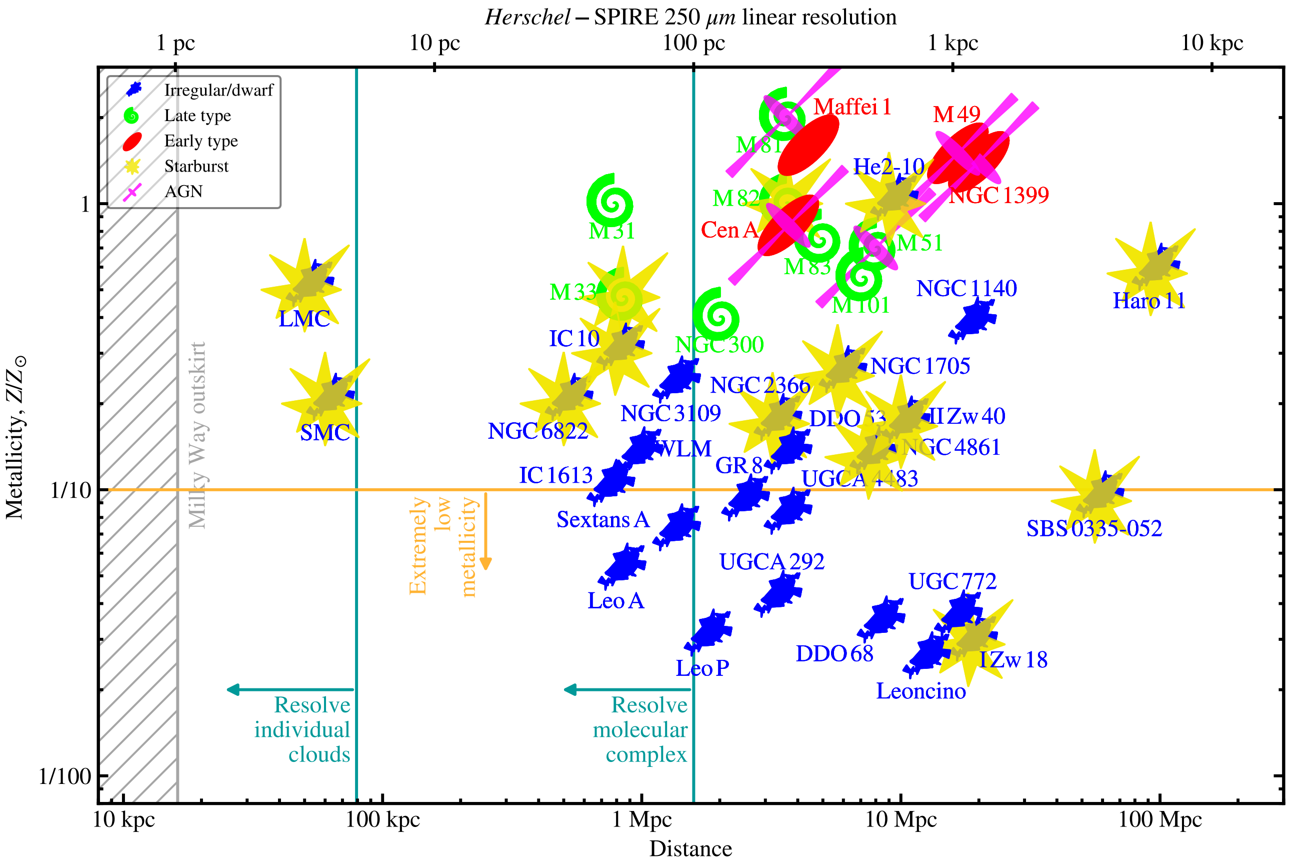

Fig. 1. This figure illustrates the diversity of nearby galaxies, their Hubble type, star-formation activity, the presence of an Active Galactic Nucleus (AGN), as a function of distance and metallicity. This is only a small sample, the volume represented here actually contains thousands of objects.

2 The diversity in the nearby Universe dust properties

2.1 Extinction curves

Historically, the presence of dust in the ISM was first inferred through extinction (Trumpler 1930). It is only with the opening of the InfraRed (IR) window, with IRAS (Neugebauer et al. 1984), that we gained access to its thermal emission. UV-visible extinction curves have been well-studied in the Milky Way. Their shape has been shown to be consistent across most sightlines, depending only on the column density (Cardelli et al. 1989). The range of extinction curves encountered in the Milky Way is represented in grey in Fig. 2..*a*.

Extragalactic extinction curves can only be measured in the most nearby systems, where individual stars can be resolved. The Large and Small Magellanic Clouds (LMC and SMC) are the most well-studied objects in that matter (colored curves in Fig. 2.a). The extinction curves of the LMC are consistent with that of the Milky Way, although they are on the steep side, with a systematically smaller 2175 Å bump. The metallicity of the LMC is only half Solar. However, in the SMC ($Z \simeq 1/5\ Z_{\odot}$), the extinction curves are steeper and the bump is almost completely suppressed. These peculiar properties are believed to be the result of a shift of the grain size distribution toward smaller sizes (UV-slope flattening), probably because of the enhance shattering by SuperNova (SN) shock waves, and the destruction of the carriers of the bump, mostly Polycyclic Aromatic Hydrocarbons (PAHs) and other carbon grains (*e.g.* Cartledge et al. 2005). Beyond these resolved systems, one have to model the global SED of these galaxies, mixing different stars and dust clouds. The extinction

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[*] In this article, we exclusively refers to *metallicity* as the mass fration of heavy elements in the gas phase, Z. It is $Z_{\odot} \simeq 1.3\,\%$ in the Solar neighborhood (Asplund et al. 2009).

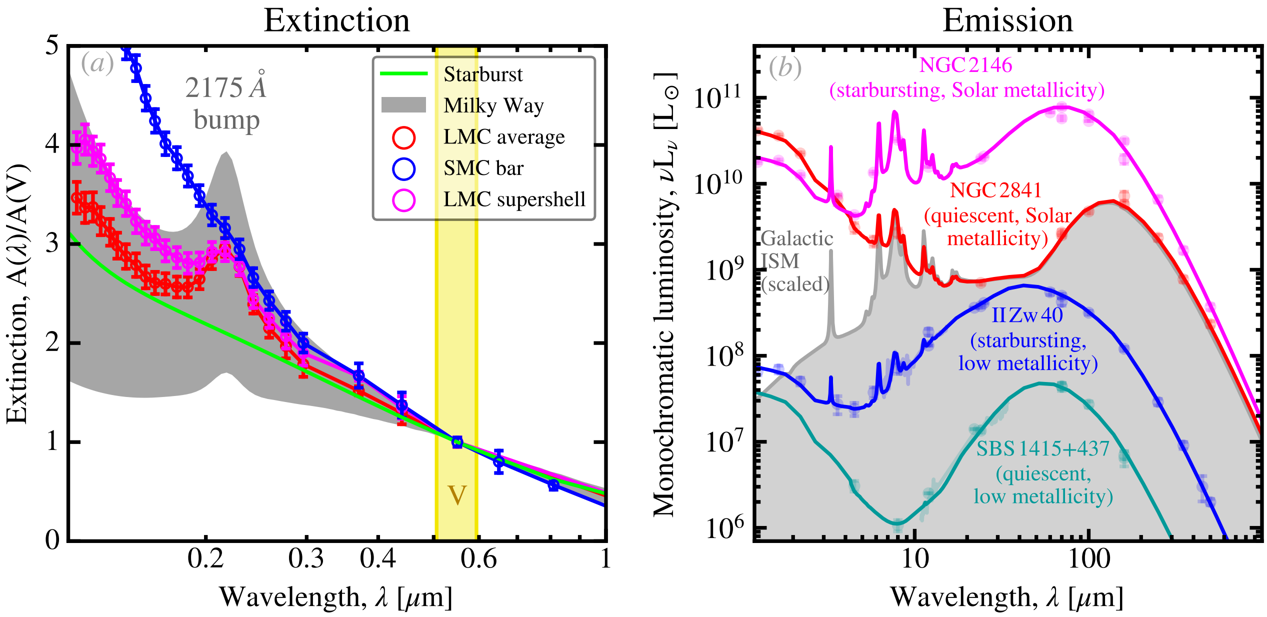

Fig. 2. Panel *(a)* compares the UV-visible extinction curves of the Magellanic clouds (Gordon et al. 2003) to the range found in the Milky Way, in grey (Fitzpatrick et al. 2019). We have also represented the starburst attenuation law of Calzetti et al. (2000), in green. The latter is not an extinction law *per se*, as it also accounts for the topology of the stellar and dust distributions. Panel *(b)* compares the IR SEDs of four nearby galaxies (Rémy-Ruyer et al. 2015) to that of the diffuse Galactic ISM (in grey). These examples illustrate the effects of metallicity and star-formation activity.

curve, which is a microscopic grain property, can thus not be easily disentangled from the macroscopic radiative transfer effects. What we obtain in these cases is an *attenuation* law.

2.2 Thermal emission

The electromagnetic power absorbed by the grains in the UV-visible is thermally re-radiated in the IR. The resulting SED is shown in grey, in Fig. 2.b, for the diffuse Galactic ISM. Large grains are at thermal equilibrium with the radiation field ($\simeq 20$ K in the diffuse ISM). They are responsible for the bulk of the far-IR emission, peaking around 120 μm. The smaller grains are however out of equilibrium, with a broader emission spectrum, fluctuating up to a few 100 K, even in the diffuse ISM (*e.g.* Galliano 2022, Chap. 1). Part of the emission of these small grains exhibit bright emission features at 3.3, 6.2, 7.7, 8.6 and 11.3 μm. These bands, and several other weaker ones, are carried by PAHs and can thus be used to quantify the abundance of this family of large molecules.

We see on Fig. 2.b that the SED of a quiescent Solar metallicity galaxy, such as NGC 2841, is identical to the Galactic diffuse ISM, apart from the stellar continuum. On the contrary, if we look at a starbursting object, such as NGC 2146, we see that the large grain emission becomes wider and peaks at shorter wavelengths. This is because the emission is now dominated by molecular clouds heated by massive stars. Low-metallicity systems are fundamentally different. A quiescent dwarf galaxy, such as SBS 1415+437, exhibits a wide and hot large grain SED, peaking around 60 μm, with a disappearance of the PAH features. The first effect is believed to result from overall smaller grain sizes, because of their shattering by numerous shock waves, and the second one because of the destruction of the PAHs by the hard, permeating radiation field (*e.g.* Galliano et al. 2005). This view is consistent with the effects we discussed earlier about extinction.

2.3 Other properties

Another important set of constraints for dust models is provided by *elemental depletions*. They quantify the amounts of individual heavy elements locked-up in grains by measuring the difference between what is observed in the gas phase and the total ISM abundances (often assumed Solar, in Galactic studies). In the Milky Way, depletions show clear correlations with the column density, suggesting that grain growth is an important process

(Jenkins 2009). In the LMC, the depletion patterns appear to be Galactic, scaled by a factor of 2 to account for the metallicity (Tchernyshyov et al. 2015). However, they systematically differ in the SMC, where the Si depletion is consistent with 0, but there is a significant Fe depletion. This property is puzzling as these two elements are believed to mainly constitute silicate grains.

Finally, the slope of the submm SED is the subject of intense debates. There appears to be a *submm excess* in some galaxies (*e.g.* Galliano et al. 2005; Bot et al. 2010), but its origin is still unknown. This feature is also seen in laboratory experiments of grain analogs (*e.g.* Demyk et al. 2017). This excess appears to be more prominent at low-metallicity, and disappears at higher metallicity. Understanding this effect is important, as its presence potentially biases the dust mass estimates derived from SED modeling.

3 Insights into cosmic dust evolution

In the Milky Way, at the scale of individual clouds, we see that the density and the radiation field control dust evolution, through the growth and removal of mantles, as well as the photo-processing of their material (*e.g.* Ysard et al. 2015). At the scale of a galaxy, when we average these local effects, metallicity appears to be the dominant parameter. This is understandable considering the peculiarity of the dust properties of low-metallicity systems we have briefly reviewed in Sect. 2. We can use nearby galaxies as snapshots of galaxy evolution at different stages in order to constrain the dust build-up and destruction over cosmic times.

3.1 Scaling relations

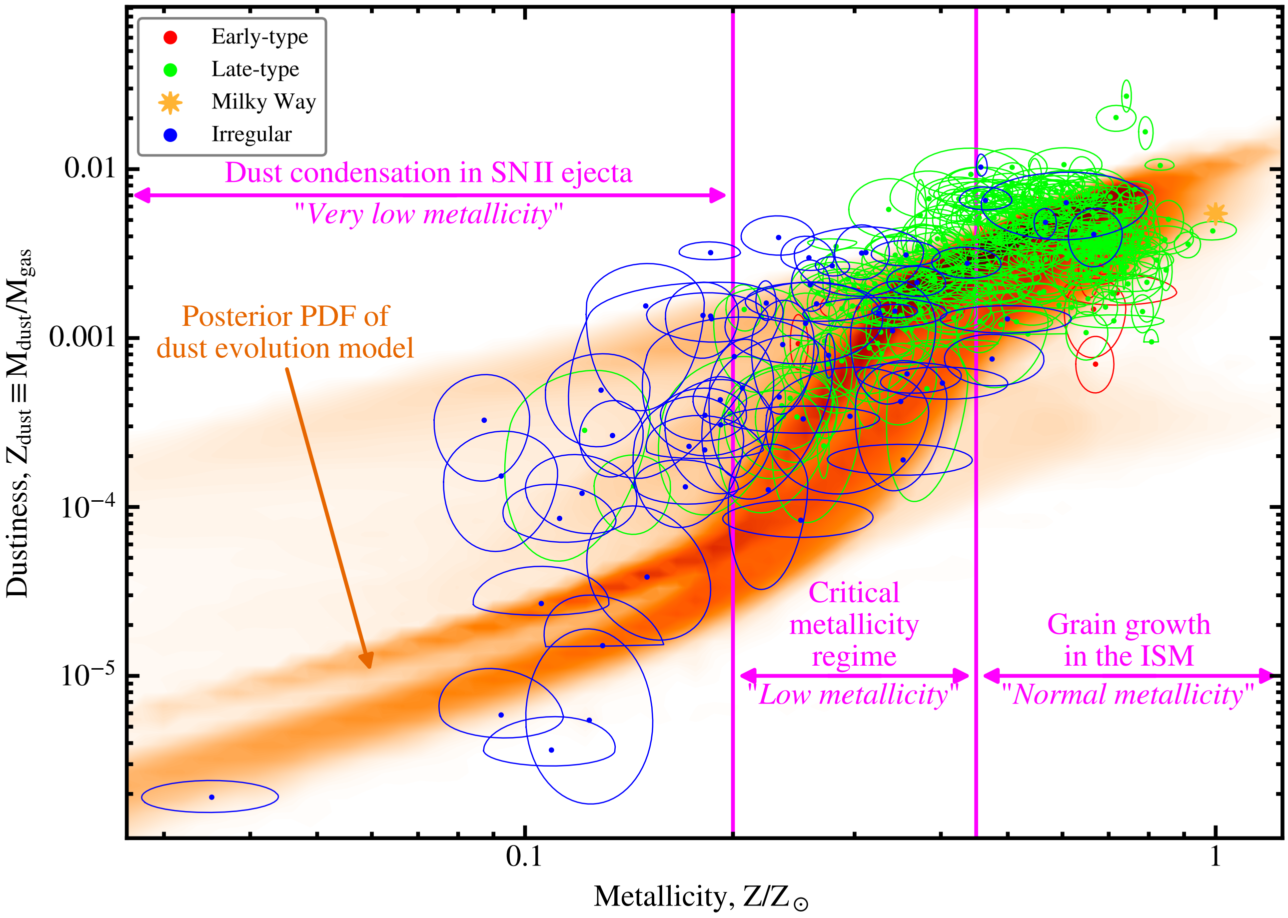

Fig. 3. The ellipses represent observations of integrated nearby galaxies (Galliano et al. 2021). The different colors correspond to different Hubble types. They are overlaid on top of the posterior Probability Distribution Function (PDF) of a dust evolution model (orange to red density) inferred from this data sample. We have delineated the three regimes discussed in the text.

The SED modeling of nearby galaxies provides estimates of the dust mass, as well as the star-formation rate and stellar mass (*e.g.* Nersesian et al. 2019). With ancillary data, we can also obtain the gas mass (atomic and molecular) and the metallicity of each object. We thus have enough data to constrain the evolution of these different parameters. Fig. 3 shows an important scaling relation between the *dustiness* (dust-to-gas mass ratio) and the metallicity. We see a rising trend indicating that the more metallic, the more dusty the ISM will be. We also see that this trend is strongly non-linear, suggesting the efficiency of the net grain production depends on the metallicity. Such a trend can be interpreted with a simple dust evolution model.

3.2 Dust evolution models

Dust evolution models follow the variations of the masses of gas, stars, heavy elements and dust of a galaxy, as a function of time, for a given star formation history (*e.g.* Dwek 1998). They account for: *(i)* the gas consumption by star formation; *(ii)* the injection of gas, heavy elements and dust by stars at the end of their lifetime; and *(iii)* the grain growth in the ISM and grain destruction by SN shock waves. They can be simple one-zone models or can be used to post-process numerical simulations of galaxy evolution (*e.g.* Aoyama et al. 2017). Their parameters can be inferred to fit scaling relations, such as demonstrated by the orange-to-red density in Fig. 3.

3.3 The three dust evolution regimes

Fitting dust evolution models to nearby galaxy scaling relations provide clear insights on the importance of different dust evolution processes as a function of metallicity (Rémy-Ruyer et al. 2014; De Vis et al. 2017; Galliano et al. 2021). This is demonstrated in Fig. 3.

At very low-metallicity ($Z \lesssim 0.2\ Z_\odot$) the dustiness is proportional to Z. Dust production appears to be dominated by its condensation in the ejecta of core-collapse SNe.

At low-metallicity ($0.2\ Z_\odot \lesssim Z \lesssim 0.45\ Z_\odot$) there is rapid rise of dustiness in a rather narrow range of metallicity (called the critical metallicity Asano et al. 2013). This is because the abundance of heavy elements in the gas phase is now sufficient for grain growth in the ISM to start dominating the dust production.

At normal metallicity ($Z \gtrsim 0.45\ Z_\odot$) the dustiness becomes roughly linear with metallicity as grain growth is now the dominant production process. This process is very efficient and has a timescale of the order of $\simeq 50$ Myr. Beyond $Z \simeq 1\ Z_\odot$, it starts tipping because of the more pronounced effects of grain destruction by shock waves.

These results suggest that massively dusty galaxies in the early Universe, could have seen their dust content produced rather fast ($\simeq 50$ Myr) by grain growth in the ISM, provided that the first wave of stars has enriched the ISM above the critical metallicity. The measurement of the metallicity of these objects with the JWST should clarify this hypothesis. We see that low-metallicity galaxies, which are the only objects we can study with enough details, are crucial to understand the early stages of dust evolution.

4 Conclusion

The overview we have brushed shows that there are several limitations that need to be addressed to progress in this field.

1. The only physical dust models currently available are all constrained by observations of the diffuse Galactic ISM. In principle, it should be possible to put together a consistent set of constraints of the extinction, emission and depletions of the Magellanic clouds. The most challenging aspect of this prospect would be to obtain clean IR SEDs of the diffuse ISM of these galaxies, where extinction and depletions have also been observed. Thia would allow us to build extragalactic dust models,

2. As we have discussed in Sect. 2, the submm excess is a puzzling open question. It can however be studied more thoroughly than before thanks to the new generation of ground-based submm/mm facilities (such as NIKA2; Catalano et al. 2018). Combined with existing *Spitzer* and *Herschel* observations it is allowing us to model the SED in a statistical sample of $\simeq 100$ pc-size regions and thus understand how this excess depends on the physical conditions (density, radiation field, *etc.*).

3. Another limitation we have briefly mentioned is the fact that we are compelled to neglect local dust evolution, as a function of density and radiation field intensity, in the extragalactic regions we model. This is because we do not have yet an accurate quantification of the timescales of the different processes controlling this local dust evolution. Observations with JWST could be enlightening to understand the evolution of small grains throughout the ISM.

4. Fig. 1 shows there is a population of quiescent, extremelly-low-metallicity galaxies. These objects have not been detected with *Spitzer* and *Herschel*, but they could help us to remove the degeneracy between the effects of metallicity and star formation activity that are always mixed when studying actively star-forming dwarf galaxies. A sensitive far-IR space observatory, such as PRIMA (Glenn et al. 2021), could make these studies possible.

To go further, my habilitation thesis (Galliano 2022) provides a comprehensive presentation of the subject discussed in this article, in a text-book format, including reminders of the elementary physical processes, a historical perspective, and an almost exhaustive review of the observations and modeling techniques.

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References

Aoyama, S., Hou, K.-C., Shimizu, I., et al. 2017, MNRAS, 466, 105

Asano, R. S., Takeuchi, T. T., Hirashita, H., & Inoue, A. K. 2013, Earth, Planets, and Space, 65, 213

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481

Bot, C., Ysard, N., Paradis, D., et al. 2010, A&A, 523, A20+

Burgarella, D., Nanni, A., Hirashita, H., et al. 2020, A&A, 637, A32

Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682

Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245

Cartledge, S. I. B., Clayton, G. C., Gordon, K. D., et al. 2005, ApJ, 630, 355

Catalano, A., Adam, R., Ade, P. A. R., et al. 2018, Journal of Low Temperature Physics, 193, 916

De Vis, P., Gomez, H. L., Schofield, S. P., et al. 2017, MNRAS, 471, 1743

Demyk, K., Meny, C., Leroux, H., et al. 2017, A&A, 606, A50

Draine, B. T. 2003, ApJ, 598, 1017

Dwek, E. 1998, ApJ, 501, 643

Fitzpatrick, E. L., Massa, D., Gordon, K. D., Bohlin, R., & Clayton, G. C. 2019, ApJ, 886, 108

Galliano, F. 2017, Planet. Space Sci., 149, 38

Galliano, F. 2022, A nearby galaxy perspective on dust properties and their evolution (HDR, Université Paris-Saclay)

Galliano, F., Galametz, M., & Jones, A. P. 2018, ARA&A, 56, 673

Galliano, F., Madden, S. C., Jones, A. P., Wilson, C. D., & Bernard, J.-P. 2005, A&A, 434, 867

Galliano, F., Nersesian, A., Bianchi, S., et al. 2021, A&A, 649, A18

Glenn, J., Bradford, C. M., Rosolowsky, E., et al. 2021, Journal of Astronomical Telescopes, Instruments, and Systems, 7, 034004

Gordon, K. D., Clayton, G. C., Misselt, K. A., Landolt, A. U., & Wolff, M. J. 2003, ApJ, 594, 279

Jenkins, E. B. 2009, ApJ, 700, 1299

Jones, A. P., Köhler, M., Ysard, N., Bocchio, M., & Verstraete, L. 2017, A&A, 602, A46

Nersesian, A., Xilouris, E. M., Bianchi, S., et al. 2019, A&A, 624, A80

Neugebauer, G., Habing, H. J., van Duinen, R., et al. 1984, ApJ, 278, L1

Rémy-Ruyer, A., Madden, S. C., Galliano, F., et al. 2014, A&A, 563, A31

Rémy-Ruyer, A., Madden, S. C., Galliano, F., et al. 2015, A&A, 582, A121

Tchernyshyov, K., Meixner, M., Seale, J., et al. 2015, ApJ, 811, 78

Trumpler, R. J. 1930, PASP, 42, 214

Ysard, N., Köhler, M., Jones, A., et al. 2015, A&A, 577, A110