Mapping Extragalactic Dust with Multi-Wavelength Imaging of Backlit Galaxy Pairs

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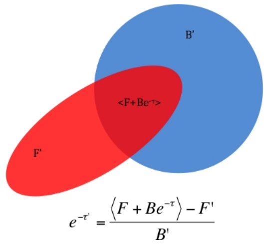
ABSTRACT

We present an on-going project combining Spitzer IRAC imaging with HST/ground-based optical imaging to characterize the properties of dust in low-redshift normal galaxies beyond the local group. The extragalactic dust is directly probed by utilizing partially superposed galaxy pairs, in which the foreground galaxy dust is backlit by the background galaxy. While this technique has previously been applied to some galaxy pairs, it has primarily used optical-wavelength data, which is subject to substantial amounts of extinction. We improve upon these studies by additionally utilizing IRAC 3.6 and 4.5 micron images which provide essentially un-extinguished reference images, and thus allow us to determine dust extinction more accurately across different parts of the foreground galaxies. Furthermore, we have studied a sample of local galaxy pairs spanning a broader range of morphologies. The very local nature of our sample allows a detailed look at dust properties at different positions within the galaxies, and facilitates an examination of what galaxy properties drive the variation in dust properties. We plan to specifically (1) address the opacity of sample spiral disks as a function of position within the galaxy disk; (2) examine whether the average dust grain size decreases in the outer parts of disks; (3) characterize the large-scale dust structure in a sample of elliptical galaxies; and (4) assess whether dust exhibits fractal structure.

METHODOLOGY

The occulting galaxy method (White & Keel 1992) exploits assumed galaxy symmetry in a partially-overlapping, superposed galaxy pair, in order to isolate the foreground galaxy "backlit" dust absorption in the overlapping region. The surface brightness in this overlap-region is taken to be $F+Be^{-\tau}$, where F and B are the surface brightnesses of the foreground and background galaxies, respectively. These components are removed by assuming that the surface brightness distribution in the non-overlapping portions of the galaxies are identical to those in the obscured, overlapping region. The foreground and background light can be estimated either by assuming rotational or reflection symmetry, or by modeling the predicted surface brightness distribution from the non-overlapping galaxy isophotes. Holwerda et al. 2009 have found that this latter method provides superior optical depth constraints, given high-quality data. This technique only requires structural symmetry in both the foreground and background galaxies; background elliptical and foreground grand-design spirals have provided the greatest success in existing studies. A schematic illustration of this technique is shown in Figure 1.



$$e^{-\tau'} = \frac{\langle F + Be^{-\tau}\rangle - F'}{B'}$$

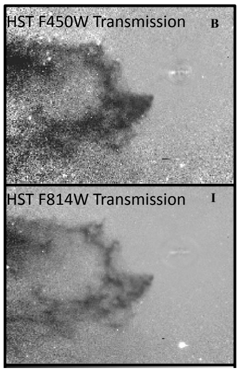


Figure 1: (above) schematic illustration of occulting galaxy method, adapted from White & Keel 1992; Holwerda et al. 2009. The resultant $e^{-\tau}$ transmission map constrains the foreground galaxy opacity, as a function of position, as shown (right) for AM 1316-241 (Keel & White 2001).

APPLICATIONS OF METHOD: optical

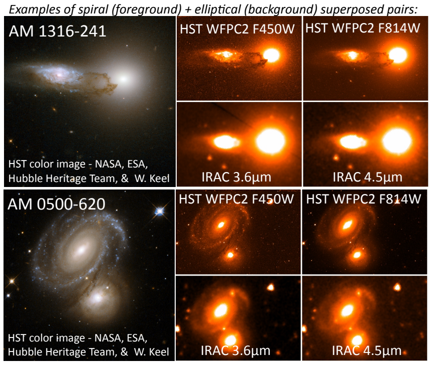
The occulting galaxy technique has been applied to ~15-20 galaxies using multi-wavelength optical data. These analyses have found:

- Substantial extinction in spiral features, in same locus as luminous stellar emission (e.g. White & Keel 1992)
- Modest interarm extinction in spiral galaxies (e.g. Berlind et al. 1997; White et al. 2000)
- Some disks have flatter/steeper extinction curves than our Galaxy – indicative of clumpy dust distributions (e.g. White et al. 2000, Keel & White 2001)
- Dust in some spirals exhibits fractal-like structure (e.g. Keel & White 2001)
- Dust disks which are more extended than the stellar disks have been found in some spirals (e.g. Holwerda et al. 2009)

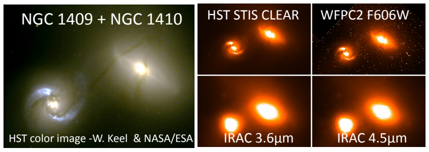
IRAC data

We have obtained IRAC 3.6 & 4.5 µm images of 16 superposed galaxy pairs, with foreground galaxy z≤0.04. These nearly un–extinguished reference images provide a comparison with the existing optical images, and produce a more accurate determination of the dust extinction across different regions of the foreground galaxies. Our sample spans a range of foreground-background morphological combinations, including 4 S-E pairs, 1 E-S0 pair, 4 S-S pairs, 3 E-S pairs, 1 S-Irr pair, and 3 E-E pairs. These allow us to constrain the large-scale properties of dust in a variety of galactic environments. A subset of the sample galaxy pairs are illustrated in Figure 2.

Examples of spiral (foreground) + elliptical (background) superposed pairs:



Example interacting superposed pair:



Example elliptical-elliptical superposed pair, NGC 4782-4783:

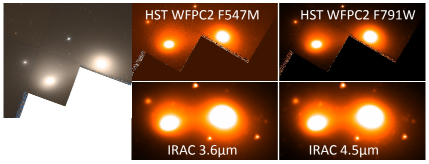


Figure 2: HST optical and IRAC infrared images for a subset of our sample. All images, other than the multi-color pictures, are shown with false color to emphasize features. Note that the prominent dust features, found in the spiral optical images, are absent in the IRAC bands. Our tests find that even when the lower resolution of the IRAC images is accounted for, there is no significant trace of these structures.

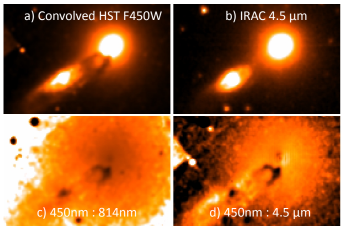


Figure 3: IRAC data for AM1316-241 compared with HST data (a) Top Left: HST F450W image of Keel & White (2001) convolved with the Spitzer IRAC FWHM at 4.5 µm for comparison. (b) Top Right: IRAC 4.5 µm image. (c) Bottom Left: HST 450 nm to 814nm ratio (d) Bottom Right: HST 450 nm to IRAC 4.5 µm ratio. Note the much smaller extinction in the overlapping region at 4.5 µm than at 450 nm.

1. Opacity of Spiral Disks

GOAL: improve the determination of the dust extinction as a function of position within spiral disks.

MOTIVATION: Previous studies of overlapping galaxies suggest that spirals are semitransparent, with opacity being higher in the spiral arms which also produce much of the light. Our proposed 3.6 and 4.5 µm images, nearly free of extinction effects, offer a more accurate reference to determine dust opacity than is possible using B and I band data (or even B and K band data).

IMPLEMENTATION: Apply occulting galaxy method similarly to optical and IR data, and compare transmission images as a function of position. A comparison of the derived extinction/reddening curves will be made with models for dust properties & Galactic observations (e.g. Cardelli et al. 1989; Indebetouw et al. 2005). As illustrated in Figure 3, 4.5µm data give a better reference to assess the extent of the dust extinction than e.g. F814W.

2. Dust Grain Size vs Disk Position

GOAL: examine whether dust grain sizes decrease in the outer parts of spiral disks

MOTIVATION: Zasowski et al. (2009) suggest increasing IR extinction and decreasing mean dust grain size in the outer parts of the MW plane.

IMPLEMENTATION: Examination of the optical depth and dust mass column densities derived from the transmission maps, as a function of the galactocentric position in the galaxy, and an examination of the extinction curves (derived above) for different regions in the spiral disks. An assessment of whether the extinction curves are steeper/flatter as a function of position, in combination with models, with allow for a characterization of the relative dust grain sizes as a function of position.

3. Large Scale Dust Structure in Ellipticals

GOAL: probe dust extinction in several elliptical galaxies

MOTIVATION: It has become evident over the past few decades that elliptical galaxies contain some cold interstellar matter (e.g., Knapp 1999). Dust lanes are prominently seen in some ellipticals, and have been found in the inner regions of a substantial fraction of ellipticals (e.g., van Dokkum & Franx 1995). Indeed, mid and far-IR emission has been detected toward a significant fraction of early-type galaxies, but it is difficult to separate the contribution of interstellar dust from that of stars and circumstellar dust. Furthermore, neither the dust lanes nor the IR emission can trace dust at large distances from the galaxy centers.

IMPLEMENTATION: Our sample includes several pairs with foreground ellipticals, for which we can directly trace dust in the outer parts by virtue of having background galaxies against which to measure extinction. An examination of color maps combining our dust-free IR data with optical data, will allow us to quantify the amount of dust in the outer regions of the galaxies.

No significant dust features have been found for NGC 4782/4783, an elliptical pair with a common envelope, based on a comparison of HST F547M and F791W data with IRAC 3.6 and 4.5 µm images. There may be a few small patches of dust in the outskirts which we are in the process of verifying.

4. Fractal Structure in Dust

GOAL: examine whether dust exhibits fractal structure

MOTIVATION: The shape of ISM structures determine the rate at which they can exchange energy and matter with their surroundings. Fractal structures evolve more quickly than smooth structures, which can affect the distribution of heat and metals in a galaxy. Given that H I distributions in several nearby galaxies are fractal (e.g., Westpfahl et al. 1999; Elmegreen et al. 2001), it is interesting to examine whether dust maps created by comparing mid-IR and optical data also exhibit fractal structure. Keel & White 2001 have found evidence for fractal structure in the dust of some spiral galaxies, using HST images of superposed galaxy pairs.

IMPLEMENTATION: We will apply a perimeter-scale test, using the box-counting procedure (e.g., Vogelaar & Wakker 1994, Westpfahl et al. 1999, Keel & White 2001), to the contours of the dust extinction/transmission maps combining the IRAC un-extincted data with the HST images.

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