Extraplanar Dust in Spiral Galaxies: Observations and Implications

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Abstract.
Recent optical and submillimeter observations have begun to probe the existence of dust grains in the halos of spiral galaxies. I review our own work in this area which employs high-resolution optical images of edge-on spiral galaxies to trace high-$z$ dust in absorption against the background stellar light of the galaxies. We have found that a substantial fraction of such galaxies ($>50\%$) show extensive webs of dust-bearing clouds to heights $z > 2$ kpc. Extraplanar dust in galaxies is statistically correlated with extraplanar diffuse ionized gas, though there is no evidence for a direct, physical relationship between these two phases of the high-$z$ interstellar medium. The dense high-$z$ clouds individually have masses estimated to be $>10^5 - 10^6 M_\odot$. The detailed properties of the observed dust structures suggest the clouds seen in our images may represent the dense phase of a multiphase ISM at high-$z$. Such dense clouds can have an important effect on the observed light distribution in spiral galaxies. I discuss the effects such high-$z$ dust can have on quantitative measures of the vertical structure of stars and ionized gas in edge-on systems.

1. Introduction

Dust in the thin disks of spiral galaxies gives rise to substantial extinction, and the effects of this extinction dominate the optical appearance of spirals when viewed edge-on. Recent work in the optical and submillimeter wavebands has shown that dust grains are not only to be found in the thin disks, but also far into the thick disks and halos of spiral galaxies (Zaritsky 1994; Alton et al. 1998; Block et al. 1999). The energy input associated with star formation in spiral galaxies can expel dust grains and gas from their disks to the surrounding interstellar halos. The expulsion of grains from the disks of galaxies can be driven by violent hydrodynamical processes (e.g., Norman & Ikeuchi 1989) or more quiescent processes such as radiation pressure (e.g., Davies et al. 1998). This expulsion of gas and the heavy element-rich dust grains from the disks of galaxies may have important implications for the chemical evolution of intracluster or intergalactic media (Wiebe et al. 1999). Furthermore, if the dust is present in great enough quantities it can have important effects on the perceived distribution of light. But, until recently, little was known of the dust content of the interstellar medium (ISM) far above the planes of galaxies.
In Howk & Savage (1997, hereafter Paper I), we presented high-resolution optical images of the nearby edge-on spiral galaxy NGC 891 taken with the WIYN 3.5-m telescope. These images reveal an extensive web of high-z dust structures seen in absorption against the background stellar light of the bulge and thick stellar disk. Figure 1 shows a deep WIYN V-band image of NGC 891 (top panel; adapted from Howk & Savage 1999b, hereafter Paper III). The absorbing dust structures are seen all along the imaged portion of the galaxy to heights approaching \( z \sim 2 \text{kpc} \). These dust-bearing clouds are optically thick and each contain significant amounts of mass (\( \geq 10^5 - 10^6 \text{M}_\odot \)) and very likely contain molecular material.

In this contribution I review our current understanding of the physical and statistical properties of such high-z clouds in spiral galaxies (§2). I also discuss the effects of these opaque high-z dust clouds on quantitative measures of galaxy structure (§3).

2. Extraplanar Dust in Normal Spiral Galaxies

2.1. Observations

In this section I summarize the observational state of our knowledge of high-z dust-bearing clouds like those seen in Figure 1 and discuss briefly our theoretical understanding of these structures. Our current observational understanding of extraplanar dust in normal spiral galaxies can be briefly summarized in three primary conclusions:

1) The observable dust-bearing clouds are clumpy and highly structured and can be viewed to heights \( z \lesssim 2 \text{kpc} \); they have large opacities and likely trace large amounts of mass.

Figure 1 shows that the distribution of high-z absorbing material in NGC 891 is complex. In a few cases the dust structures seem obviously to be tracing disk-halo outflows or interactions. However, the vast majority of the observable dust clouds show no immediate morphological connection with canonical chimney or superbubble phenomena (see Paper I).

The absorption due to this high-z dust is significant, with each of the hundreds of dust-laden structures providing \( A_V \gtrsim 1 \text{mag} \). These dust-bearing clouds, if they have Galactic dust-to-gas ratios, have masses \( \gtrsim 10^5 - 10^6 \text{M}_\odot \), similar to the Galactic giant molecular clouds. As an ensemble the clouds likely contain \( \gtrsim 10^8 \text{M}_\odot \), or approximately the
same amount of mass as the diffuse ionized gas (DIG; Dettmar 1990). The maintenance of such an extended layer of dusty material requires a significant amount of energy: the gravitational potential energy for each cloud is $> 10^{52}$ ergs (Paper I). Though our data are deep enough to reveal such clouds, there is a real paucity of structured dust-laden clouds at heights $z \gtrsim 2$ kpc (Paper III).

2) **Extraplanar dust-bearing clouds are a common feature of spiral galaxies, and their existence is statistically correlated with the presence of extraplanar diffuse ionized gas.**

In Howk & Savage (1999a, hereafter Paper II) we presented short observations of all the *truly* edge-on, massive northern spiral galaxies within 25 Mpc. Table I lists the seven such galaxies, and indicates
Table I. Dust and DIG Properties for Edge-On Galaxy Sample

| Galaxy     | \(L_{FIR}/D_2^2\) (10^{40} \text{ erg/s kpc}^2) | High-z Dust | High-z DIG | DIG Ref. |
|------------|-----------------------------------------------|-------------|-------------|---------|
| NGC 891    | 3.3                                           | ⬤           | ⬤           | 1,2     |
| NGC 4013   | 2.6                                           | ⬤           | ⬤           | 3       |
| NGC 4302   | \(<2.3\)                                       | ⬤           | ⬤           | 3       |
| NGC 3628   | 1.8                                           | ⬤           | ⬤           | 4       |
| NGC 5907   | 0.8                                           | ○           | ○           | 3       |
| NGC 4565   | 0.3                                           | ○           | ○           | 5       |
| NGC 4217   | \(<0.12\)                                      | ⬤           | ⬤           | 3       |

\(a\) – ⬤ denotes galaxies that exhibit high-z dust in WIYN images; ○ denotes galaxies that do not exhibit high-z dust in WIYN images.

\(b\) – ⬤ denotes galaxies with observable high-z DIG; ○ denotes galaxies for which H\(\alpha\) searches have not shown detectable high-z DIG.

REFERENCES: (1) Dettmar (1990); (2) Rand et al. (1990); (3) Rand (1996); (4) Fabbiano et al. (1990); (5) Rand et al. (1992)

whether they show evidence for extraplanar dust. Also indicated is the presence or absence of extraplanar DIG. The galaxies in this table are listed in order of decreasing far-infrared luminosity per unit disk area, a rough indicator of the star-formation rate per unit area.

Though there are a small number of truly edge-on galaxies in the survey volume, Table I shows a large fraction of local universe spirals contain extraplanar dust. Furthermore, there is a one-to-one correlation between the presence (or absence) of extraplanar dust and the presence (or absence) of extraplanar DIG. Figure 2 shows a WIYN unsharp-masked V-band image of NGC 4013 (Paper II). The dust structures in this system have similar properties to those seen in NGC 891 (see Paper II). Given the short exposure times required to identify such high-z absorbing structures, using dust as a tracer of interstellar matter in galaxy halos is much more efficient than H\(\alpha\) imaging.

3) There is NO evidence for a direct physical relationship between the dust-bearing clouds and the DIG seen in galaxy halos.

Though there is a striking statistical correlation between the presence of high-z dust and DIG in spiral galaxies (Paper II), the morphology of the dust and the DIG are extremely different. The H\(\alpha\) emission from the halo of NGC 4013 (Rand 1996) is localized to only a few patches, and seems to be more smoothly distributed within those
patches, whereas the high-$z$ dust absorption is visible along most of the length of the galaxy and is highly structured.

A more detailed, direct comparison between the H$_\alpha$ and dust morphologies for NGC 891 is given in Paper III. Figure 1 shows an unsharp-masked version of the WIYN H$_\alpha$ image immediately below the V-band unsharp-masked image. Comparing the two images in Figure 1, one is left with the (correct) impression that the H$_\alpha$ distribution is much smoother with less pronounced, and fewer, filamentary structures.

2.2. INTERPRETATION

The comparison of the H$_\alpha$ and broadband data for NGC 891 (Paper III) suggest that we are observing two distinct “phases” of the ISM with these two probes of thick disk matter. The H$_\alpha$ images trace an ionized, low-density medium, while the dust structures seen in absorption are tracing a dense, neutral phase of the high-$z$ ISM. In standard models of thermal phase equilibrium for disk of the Milky Way, a dense phase of the ISM is present only if the pressure of the medium is high enough (e.g., Wolfire et al. 1995). Rough calculations of the pressure distribution of the DIG and hot ISM in NGC 891 suggest that these media provide a sufficient external pressure to allow for the existence of a dense neutral phase (see Paper II). That virtually no clouds are observable at heights in excess of $z \sim 2$ kpc may imply that the pressure is insufficient to support the dense clouds above this height. If this is
the case, there may very well be unobserved dust at heights in excess of 2 kpc (our images are only sensitive to clouds that are overdense relative to their surroundings). In general we do not expect a cold, neutral phase of the ISM at high-z to be directly associated with the extraplanar DIG.

The interpretation that the observed dust clouds represent the dense phase of a multiphase medium at high-z is also supported by two recent observational results. García-Burillo et al. (1999) have presented high-resolution CO maps of the inner portion of NGC 4013 showing extraplanar CO features far above the plane of the galaxy. *Many of these CO features are directly associated with high-z dust structures observable in our WIYN images.* The presence of a dense phase of the thick disk ISM is also implied by our own discovery of H II regions far above the planes of NGC 891 and NGC 4013 (see Paper III). In NGC 891 these candidate nebulae are associated with faint, blue continuum sources at heights $0.5 \lesssim z \lesssim 2.0$ kpc. These objects likely represent young stellar associations formed far above the plane of the galaxy, perhaps in the dense clouds visible in our WIYN images.

3. Extraplanar Dust and the Vertical Light Distribution in Spiral Galaxies

The presence of dense dust-laden (molecular) clouds in the thick interstellar disks of spiral galaxies affects the perceived vertical distribution of light in these systems. The absorption due to these clouds will not only affect the perceived distribution of stellar light, but will also affect light produced by the high-z gas layers (e.g., Hα or X-ray emission). In Paper III we have shown that much of the structure perceived in the Hα emission from the DIG at heights $z \lesssim 1.0$ kpc from the midplane of NGC 891 is caused by the patchy absorption of these dense clouds.

Figure 3 shows the vertical light distribution for a region near the center of NGC 891, averaged over 45 pc in the radial direction and normalized to the intensity of each bandpass at $z = 2$ kpc. The impact of discrete absorbing clouds can be seen in these vertical cuts. For example, quite prominent dust structures are intercepted at $z \sim 1.2$ kpc. One can see by comparing the B- and I-band curves in Figure 3 that the distribution of light at heights $z \lesssim 0.75$ kpc is severely affected by the presence of extraplanar interstellar dust. Fits to the light distribution at heights less than this will be dominated by dust absorption. Figure 3 also shows that NGC 891 gets *bluer* with distance from the midplane to a height of $z \sim 1.9$ kpc, indicating that large amounts of dust are present at great heights.
Most studies of the structure of nearby galaxies employ images taken in much poorer seeing than ours. This has the effect of washing out the discreet, small-scale dust structures. Typical high-\(z\) dust features in the thick disk of NGC 891 have minor axis sizes of order 100 pc (\(<\simeq 2''\)). Images taken in seeing \(\simeq 1''5\) show relatively little direct evidence for the widespread, complicated distribution of dust seen in our higher resolution data.

The high-\(z\) dust structures have two important effects on the perceived vertical distribution of light. First, it tends to flatten the observed distribution of emission, making the scale height of the light seem larger than the true scale height. Second, since the dust is more prevalent at low \(z\)-heights, it can also cause two distinct vertical components (e.g., thin and thick disks) to appear as one in lower resolution data. Single exponential fits to smoothed versions of our WIYN B-band data (simulating seeing of 1''5), for example, yield a scale height \(h_z = 1.05 \pm 0.04\) kpc with a linear correlation coefficient \(r = 0.995\) (fitting only the light above \(z = 1.0\) kpc in log space). The true distribution of emission, however, is likely similar to the I-band, where two components are clearly seen: a thin disk whose scale height is uncertain
because of the dust (Xilouris et al. 1998 derive $h_z \approx 0.3$ kpc) and a thick disk with scale height of order $h_z \sim 1.7$ kpc (Morrison et al. 1997).

It is likely that extraplanar dust significantly affects the perceived distribution of light away from the midplanes of spiral galaxies.

The effects of extraplanar dust on the perceived light distribution in spiral galaxies can be extremely important for studies attempting to derive fundamental morphological properties of these systems. This is true for studies of the starlight as well as studies of emission from the ISM above the planes of spirals, including Hα and soft X-ray emission.

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