Extraplanar Dust: a Tracer of Cold Dense Gas in the Thick Disks of Spiral Galaxies

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Abstract.
The interstellar thick disks of galaxies contain not only gas, but significant quantities of dust. Most of our knowledge of extraplanar dust in disk galaxies comes from direct broadband optical imaging of these systems, wherein the dust is identified due to the irregular extinction it produces against the thick disk and bulge stars. This observational technique is sensitive to only the most dense material, and we argue much of the material identified in this way traces a cold phase of the interstellar thick disks in galaxies. The presence of a cold, dense phase likely implies the interstellar pressures in the thick disks of spiral galaxies can be quite high. This dense phase of the interstellar medium may also fueling thick disk star formation, and Hα observations are now revealing H II regions around newly-formed OB stars associations in several galaxies. We argue that the large quantities of dust and the morphologies of the structures traced by the dust imply that much of the extraplanar material in disk galaxies must have been expelled from the underlying thin disk.

1. Introduction

Understanding the structure of the gaseous component of disk galaxies is an important step for unraveling their on-going evolution. In particular, extraplanar gas in galaxies is a potentially-important probe of the effects of kinetic and radiative feedback from massive stars to the gas in galaxies, as well as of the role that the accretion of metal-poor gas plays in the evolution of modern galaxies. Most studies of extraplanar matter have focused on the gas content of the interstellar thick disks and halos of galaxies. However, the processes that transport matter from the thin disks of galaxies into the thick disks and extended halos will act on both gas and interstellar dust grains. The presence of extraplanar dust in galaxies can strongly affect the thermal balance of the gas, and it will definitely affect an observer's view of a galaxy through its impact on the transfer of radiation.

The presence of extraplanar dust in the canonical edge-on galaxy NGC 891 was noted many years ago (Sandage 1961; Dettmar 1990; Keppel et al. 1991). However, an analysis of the implications of the extensive web of dusty extraplanar material in this galaxy did not occur until recently (Howk & Savage 1997, 2000). In the last few years, extraplanar dust has been recognized and studied in many edge-on systems (Sofue, Wakamatsu, & Malin 1994; Howk & Savage 1999; Alton et al. 2000; Rossa & Dettmar 2003; Thompson, Howk, &

Savage 2004), and we now know that the presence of extraplanar dust and gas are indeed coupled.

In this contribution, I will concentrate on the physical interpretation of the observed extraplanar dust and its implications for the nature of the interstellar thick disks of spiral galaxies. In particular, I will summarize some of the evidence that material identified with extraplanar dust may represent a dense, cold medium in the thick disks of galaxies.

2. Extraplanar Dust in Spiral Galaxies

It is now established that at least $\sim 40\%$ of spiral galaxies in the local Universe show some form of extraplanar (thick disk) dust and, hence, gas (Rossa & Dettmar 2003; Howk & Savage 1999). The most common technique currently employed for identifying extraplanar dust is to image directly edge-on spiral galaxies in the optical, searching for obvious evidence of shadowing of the thick disk, halo, and bulge stars by optically-thick foreground dust. Figure 1 gives an example of this approach, showing two views of the V-band image of NGC 891 from Howk & Savage (2000). The presence of dust in the thick disk of this galaxy is obvious from these images.

From the stand-point of total exposure time required, such broadband imaging is by far the most efficient manner of finding extraplanar material in galaxies (although it does require high-resolution – $\lesssim 1''$ – imaging). The presence of extraplanar dust is likely a flag that a significant amount of extraplanar gas is present, as well. Not only is there likely to be a significant amount of gas associated with the dust structures detected through direct optical imaging, but the surveys of Rossa & Dettmar (2003) and Howk & Savage (1999) have shown that $\sim 90\%$ of galaxies exhibiting extraplanar dust also have extraplanar diffuse ionized gas (DIG) detectable through Hα emission.

While it is straightforward to note the presence of extraplanar dust from images such as that shown in Figure 1, there are several biases inherent to this approach. As discussed in Howk & Savage (2000) and more recently in Thompson et al. (2004), we are only able to detect dusty regions through direct optical imaging because of they have significantly lower surface brightness than their surroundings. This implies that the dust-bearing clouds seen in our images must have a higher column density of dust (and gas) than their surroundings: a smooth distribution of dust would produce no contrast and would be undetectable in these images. In practice this likely implies the dusty clouds are more dense than their surroundings (assuming the thick disk gas has a relatively uniform dust content). A number of other, less scientifically interesting, biases should be considered when looking at images such as those in Figure 1. The requirement of large contrast tends to bias us toward detecting dust on the near side of galaxies, and, due to signal-to-noise constraints, we are more likely to detect high-z dust in regions of intrinsically higher surface brightness (e.g., against the bright light of a galactic bulge or at lower heights above the midplane).

Using estimates of the "apparent extinctions" produced by individual thick disk dust clouds, Howk & Savage (1997, 1999, 2000) and Thompson et al. (2004) have estimated physical properties of these clouds, albeit crudely. Because the

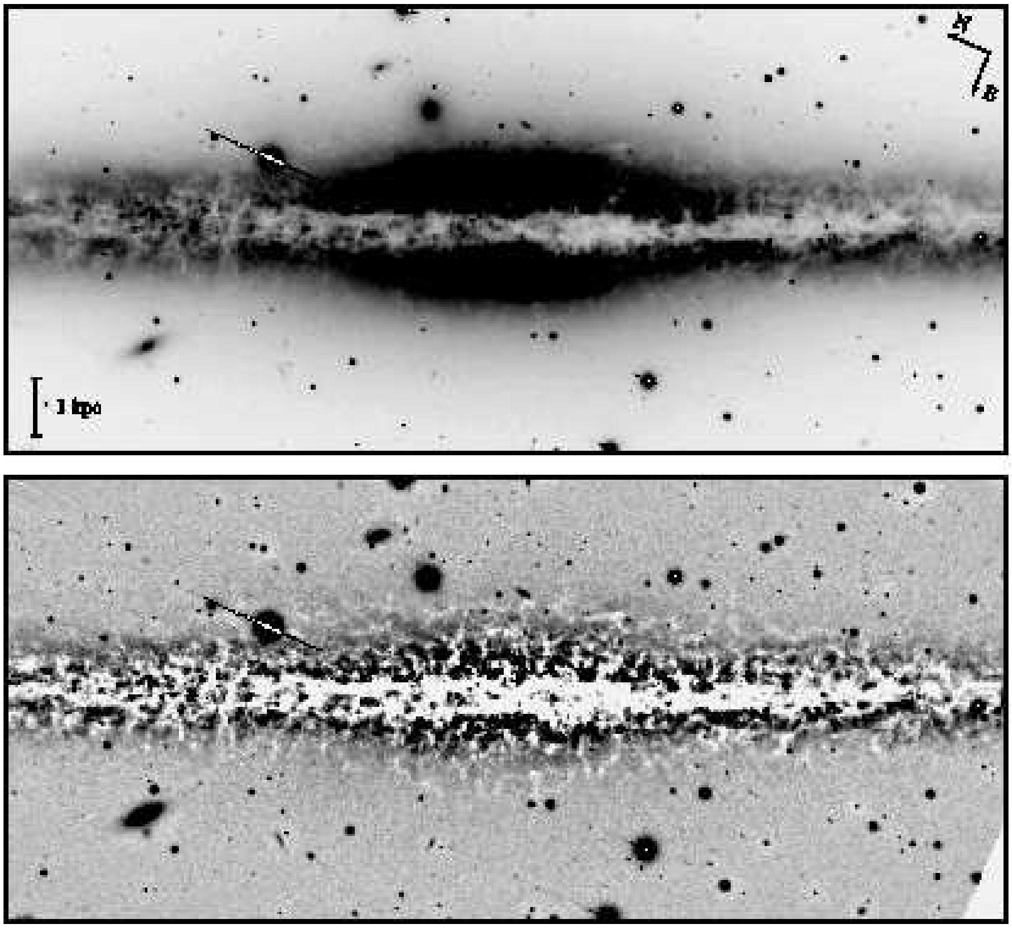

Figure 1. Two versions of a broad-band optical (V-band) image of the edge-on galaxy NGC 891 from Howk & Savage (2000). The top panel shows the direct V-band image. The bottom panel shows an unsharp-masked version of the V-band image. The latter is produced by smoothing the original image and dividing the original by this smoothed version. The purpose is to remove large-scale surface brightness variations, e.g., due to the vertically-decaying light from the stellar disk or from the bulge of the galaxy.

apparent extinctions will always underestimate the true extinctions through the clouds (see Howk & Savage 1997), all of the physical quantities derived using the apparent extinctions are lower limits. Assuming the dust-to-gas ratio in these clouds is similar to that found in the disk of the Milky Way (which is probably not too bad an assumption; Thompson et al. 2004), the dusty cloud complexes detected in our images must have $N(\text{H I}) \gtrsim 10^{20}$ cm^{-2}. Furthermore, the densities in these clouds must be quite high. Examining the apparent extinctions and sizes of the smallest structures in the extraplanar cloud complexes in NGC 891 as seen in new images from the Advanced Camera for Surveys on board the *Hubble Space Telescope* suggests the densities in these clouds may be $n_H \gtrsim 25$ cm^{-3}.

The combination of these estimated column densities and the projected sizes of the cloud complexes in our images imply total masses of $\sim 10^4$ to 10^5 $M_\odot$ or higher *in each complex*. Such masses are consistent with those of the individual giant molecular clouds in the Milky Way. In galaxies with detectable extraplanar dust, we typically find hundreds of absorbing structures at $z \lesssim 2$ kpc all along the central regions of the disk (within $R \lesssim 8$ kpc, similar to the radial extent of detectable DIG). Howk & Savage (1997) estimated the total mass of the ensemble of clouds in NGC 891 to be $\sim 10^8$ $M_\odot$, comparable to the total mass of extraplanar DIG material (Dettmar 1990).

Morphologically, the extraplanar dust structures seen in direct optical images are quite complex and varied. Much of the complexity is likely due to the observed clouds residing at different depths through a galaxy. The identification of cloud complexes which may represent coherent structures is extremely difficult at heights $z \lesssim 1$ kpc from the midplanes of spirals, particularly toward the centers of galaxies where more structures may be present along a given sight line. In fact, we believe that sight lines through an edge-on galaxy with extraplanar dust are typically optically thick for heights $z \lesssim 1$ kpc. At such heights, every sight line intercepts at least one dust-bearing cloud, each of which we believe to have $A_V > 1$. At larger heights, where the confusion is significantly lessened, it is possible to identify what appear to be individual, sometimes isolated clouds or structures. As an example of this, Figure 2 shows a portion of our *HST* image of NGC 4217 (Thompson et al. 2004). Thompson et al. note the presence of a structure that appears to be a large loop (marked in Figure 2) with diameter ~ 800 pc centered at $z \sim 1300$ pc from the midplane of this galaxy. Such a structure would be confused at lower heights from this or other galaxies. Even at the height of this structure, though, one worries that what appears to be a loop may be caused by several overlapping, but unrelated, cloud complexes.

3. Cold, Dense Gas in the Multiphase Thick Disks of Spiral Galaxies

We have argued that the dust-laden clouds identified in the thick disks of spiral galaxies through direct optical imaging represent a cold, dense phase of the thick disk ISM (Howk & Savage 1999, 2000). The derived column densities and particle densities are consistent with this picture. The high column densities we derive for many individual structures are high enough that they would have molecular fractions of $> 25\%$ if the physical conditions (i.e., dust content and radiation fields) are similar to those found in the disk of the Milky Way. There are other observational indications that, sometimes indirectly, lead us to believe the thick disks of galaxies contain a CNM that is traceable through its extinction.

First, it is clear that the interstellar thick disks of spiral galaxies are multiphase media. The observations of gas at temperatures that span several orders of magnitude (e.g., through observations of Hα and X-ray emission) in the thick disks of galaxies imply the presence of distinct interstellar phases. Howk & Savage (2000) have compared high resolution (sub-arcsecond) imaging of Hα from the extraplanar DIG and of absorption due to the extraplanar dust in NGC 891. This comparison revealed not only that the structures seen in dust and Hα are not physically related, but that the WIM is much more smoothly distributed than the material traced by dust extinction. This almost certainly implies the

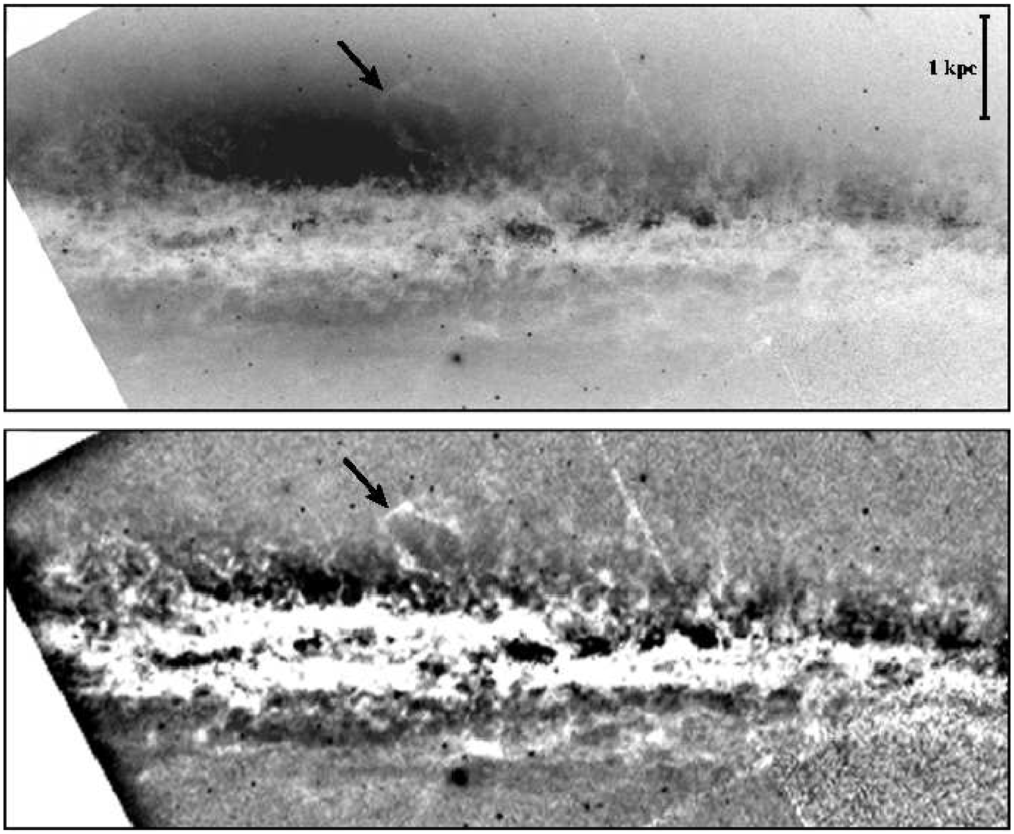

Figure 2. Two versions of a broad-band optical (B-band) image of the edge-on galaxy NGC 4217 from Thompson et al. (2004) taken with the Wide Field and Planetary Camera 2 on board *HST*. The top panel shows the direct B-band image. The bottom panel shows an unsharp-masked version of the B-band image. The large loop discussed in the text is marked with an arrow.

volume filling factor of the material traced by extraplanar dust is much smaller than that of the DIG. Rossa and collaborators (this proceedings; Rossa et al. 2004) have recently presented even higher-resolution images of NGC 891 acquired with *HST* that lead to the same conclusion: the dust and the ionized gas occupy separate regions of space with very little correspondence and, therefore, represent *distinct phases* of the multiphase thick disk in this galaxy.

There is also some evidence for CO emission, a direct tracer of CNM material, in the thick disks of spiral galaxies. García-Burillo et al. (1999) have presented CO observations of the edge-on galaxy NGC 4013. Their interferometric maps reveal the presence of CO-bearing extraplanar filaments, some of which are coincident with extraplanar dust seen by Howk & Savage (1999). This is a direct indication of the presence of a CNM in the thick disk of this galaxy. Unfortunately, few galaxies have been observed with the sensitivity and resolution required to detect these structures. NGC 891 has been mapped in CO, although the picture in this galaxy is far from clear: single-dish (García-Burillo et al. 1992) and interferometric (Scoville et al. 1993) observations give conflicting results. We are pursuing deep interferometric CO mapping of this galaxy to limit the amount of CO in the thick disk of this system.

Perhaps the least direct, but most interesting, indicator for the presence of a CNM in the thick disks of galaxies is the recent evidence for thick disk star formation in spiral galaxies. Several authors have noted the presence of extraplanar H II regions in the thick disks of galaxies (Walterbos 1991; Ferguson, Wyse, & Gallagher 1996; Howk & Savage 1997, 2000). These regions are too far from the midplanes of the host galaxies for the OB associations required to ionize the gas to have been born in the disk and subsequently ejected. The study of the abundances and stellar content of such regions has just begun (Tüllman et al. 2003) and may give us important information on the circulation of metals within the thick disks of galaxies. Indirectly, the presence of newly-formed hot stars in the thick disks implies the presence of a CNM, since the latter is a crucial ingredient for star formation. We consider it likely that the young stars have formed from clouds similar to those seen in our images.

4. Implications for the Nature of Extraplanar Matter

The presence of dust in the thick disks of galaxies has important implications for understanding the nature of extraplanar gas in spiral galaxies. Perhaps the most fundamental implication of significant amounts of dust in the thick disks of spiral galaxies is that much of the interstellar material in the thick disk in these systems has been expelled from the underlying thin disk rather than accreted from a reservoir of primordial material. This is strongly suggested by the large amounts of dust directly visible in our images. Furthermore, while not generally true, there are indeed structures connecting the extraplanar dust to the underlying thin disk (Figure 3). The precise mechanism for expelling gas and dust from the thin disk is not constrained, but some aspect of feedback from massive stars likely drives the expulsion.

The statement that much of the thick disk ISM must have been expelled from the thin disk does not necessarily constrain the nature of "halo" gas, material at very large distances from the plane. The maximum extent of dusty material observable through its optical absorption against background starlight is $z \sim 2$ kpc. This varies slightly among the observed galaxies and potentially with position in an individual galaxy. However, in the best studied case of NGC 891, there is sufficient light from the stellar bulge and thick disk that clumpy dust structures could have been seen to much larger heights in the central regions (Howk & Savage 2000).

The lack of detectable dust at larger heights has a few potential causes. Having argued the strongly-clumped dust at $z \lesssim 2$ kpc is associated with a CNM, we have suggested that the interstellar pressures at larger heights may be insufficient to support a CNM (Howk & Savage 1999, 2000). In which case, the dust at these heights is associated with a diffuse medium with little in the way of small scale, high column density structures that would be detectable via direct optical imaging. Alternatively, there could simply be a lack of dust at high-z, either due to the smaller amount of gas at such heights or a changing gas-to-dust ratio.

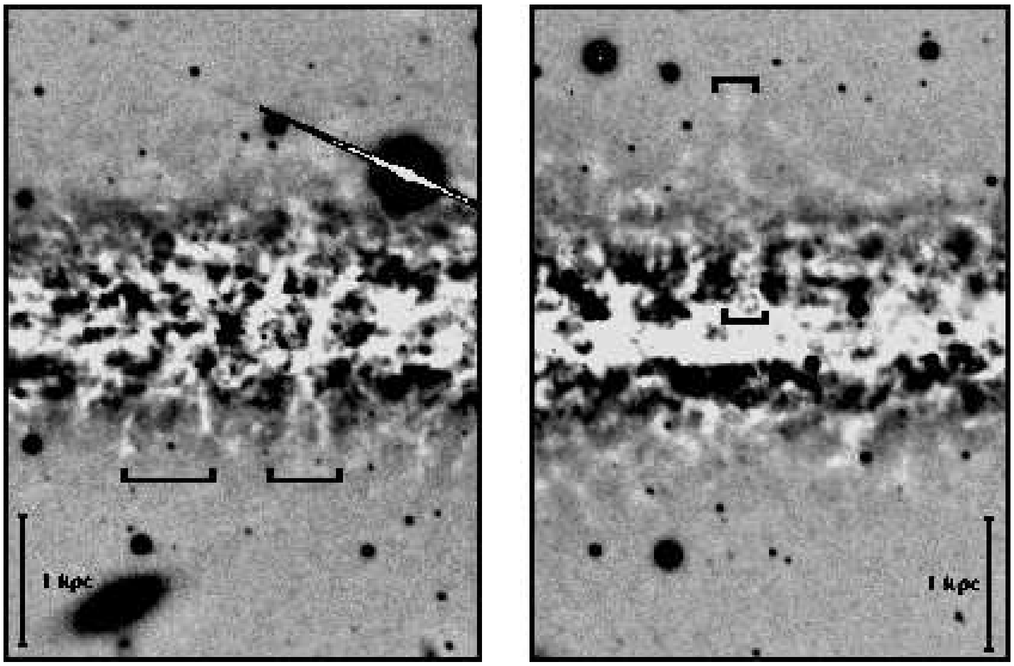

Figure 3. Sections of the unsharp-masked V-band image of NGC 891 from Howk & Savage (2000); these regions are centered to the NE (left) and SW (right) of the galaxy center. The high-z structures marked in these images are clearly connected to the disk of the galaxy. The source of thick disk dust observed in this and other galaxies is expulsion from the thin disk. The connection to the thin disk is not unique to NGC 891, but is also seen in other galaxies (e.g., Thompson et al. 2004; Sofue et al. 1994).

While the current observations do not allow us to determine which of these scenarios is more likely, up-coming observations with the *Spitzer Space Telescope* and the *Galaxy Evolution Explorer* may help by revealing a smooth component of dust at $z \gtrsim 2$ kpc in galaxies. The distinction is potentially important, as it could bear on the amount of gas contributed to modern galaxy halos by on-going infall of primordial material and on the possibility that dust (and potentially gas) may escape a galaxy's potential altogether.

It is worth noting, also, that the presence of dust grains in the thick disks of galaxies implies that the mechanisms that transport material from the thin to thick disks are not sufficiently violent to completely destroy the dust. Thus, if feedback processes are responsible for expelling the dust and gas into the thick disks of galaxies, the characteristic velocities with which much of the present thick disk matter is expelled was likely too small to produce much dust destruction. This suggests that much of the extraplanar material may be simply displaced disk gas rather than material that started as shock-heated gas and metal-enriched supernova ejecta. The lifting of material through magnetically-driven mechanisms (e.g,. the Parker instability) or other more quiescent mechanisms may be important, although they are not necessary.

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