Extraplanar Dust and Star Formation in Nearby Edge-On Galaxies

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We present high-resolution ($\lesssim 0.7'$) ground-based images of the edge-on spiral galaxies NGC 891 ($D \sim 9.5$ Mpc) and NGC 4013 ($D \sim 17$ Mpc) acquired with the WIYN 3.5-m telescope. These BVI+Hα images reveal complex webs of dusty interstellar material far above the midplanes of both galaxies ($0.5 \lesssim |z| \lesssim 2$ kpc) as discussed previously by Howk & Savage (1997). The dusty high-$z$ clouds, visible in absorption against the background stellar light of the galaxies, have widths $50$–$100$ pc and lengths $100$–$400$ pc. An analysis of their absorbing properties suggests they have $A_V \gtrsim 0.5$–$2.0$. If Milky Way gas-to-dust relationships are appropriate, then these structures have gaseous column densities $N_H \gtrsim 10^{21} \text{cm}^{-2}$, with very large masses ($\gtrsim 10^5$–$10^6 \text{M}_\odot$) and gravitational potential energies ($\gtrsim 10^{51}$–$10^{52} \text{ergs}$ relative to $z = 0$). The estimated column densities suggest molecular gas may be present, and with the estimated masses allows for the possibility of star formation in these dusty clouds. Recent star formation is the likely cause of the discrete H II regions, in some cases associated with relatively blue continuum sources, observed at heights $0.6 \lesssim |z| \lesssim 0.8$ kpc above the disks of these galaxies. The presence of early-type stars at high-$z$ in these galaxies may be related to the extraplanar dust structures seen in our images.

1. Introduction

Recent studies have shown many of the phases of the interstellar medium (ISM) found in the thin interstellar disks of spiral galaxies are also present in their extended gaseous thick disks (e.g., Dettmar, these proceedings). Galaxies which are vigorously forming stars may also be expelling a substantial amount of hot enriched gas as young massive stars evolve and die as supernovae, and the existence of thick disk gas seems to be correlated with the star formation rate of the underlying disk. The effects of supernova explosions are not, however, limited to the hot gas, but rather massive stars may be able to expel parcels of ambient gas to great heights above the planes of spiral galaxies.

Whatever the precise mechanism for supplying gas to the thick disk, it is clear that warm and hot material are found in this interface region between the thin disks and the more extended gaseous halos of galaxies. What, however, are the conditions of this material? How is the thermal and multi-phase balance of this material different than that in the disk? Are dust grains and molecules present at large distance from the plane?

We have undertaken an imaging study of several nearby edge-on spiral galaxies with the WIYN 3.5-m telescope to search for and characterize gas and dust structures in the disk-halo interface of these systems. In this contribution we present images of two of the galaxies in our study: NGC 891 and NGC 4013, extending our earlier imaging work on NGC 891 (Howk & Savage 1997; hereafter IS97). Here we briefly describe the conclusions we have drawn from our images, particularly regarding the physical properties of dusty clouds in the interstellar thick disks of NGC 891 and NGC 4013. We also comment on evidence in our images for the presence of early-type stars far above the planes of spiral galaxies.

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Table 1: Dust cloud properties in NGC 891 and NGC 4013

| Cloud | $z$ [pc] | $A_V$ [mag] | $N_H$ [cm$^{-2}$] | Mass$^2$ [$10^5$ M$_\odot$] | Energy$^{2,3}$ [$10^{51}$ ergs] |
|-------|----------|-------------|------------------|---------------------------|-----------------------------|
| 1     | 600      | 1.8         | $3 \times 10^{21}$ | 40                        | $130$                       |
| 2     | 1450     | 0.8         | $1 \times 10^{21}$ | 2                         | $25$                        |
| 3     | 600      | 0.7         | $1 \times 10^{21}$ | 8                         | $40$                        |
| 4     | 950      | 0.7         | $1 \times 10^{21}$ | 3                         | $25$                        |
| 5     | 1350     | 0.7         | $1 \times 10^{21}$ | 2                         | $30$                        |
|       |          |             |                  |                           |                             |

1 - Identification number in Fig. 1 for individual dust clouds in both galaxies.
2 - These quantities assume Galactic gas-to-dust relationships.
3 - Gravitational potential energy relative to the midplane.

2. Dusty Thick Disks in Edge-On Spirals

Using the WIYN 3.5-m telescope on Kitt Peak we have obtained high-resolution ($\lesssim 0''.7$) BVI+H$\alpha$ images of several nearby edge-on galaxies. Fig. 1 presents unsharp-masked versions of the V-band and B-band images for NGC 891 and NGC 4013, respectively. These images reveal extensive amounts of highly-structured dust seen in absorption against the background stellar light of these galaxies to heights $z \lesssim 2$ kpc from their midplanes.

An analysis of the absorbing properties of the dust in the BVI bandpasses allows us to estimate the total visual extinction, $A_V$, through the observed dust features (e.g., HS97). In Fig. 1 we have marked several individual dust structures in each galaxy; Table 1 summarizes the properties of these structures. Our analysis neglects the effects of scattering by grains, but this omission is such that our derived values of $A_V$ are lower limits. The entries given for $N_H$, mass, and gravitational potential energy in Table 1 are derived assuming Milky Way gas-to-dust relationships (e.g., Bohlin et al. 1978).

Our analysis suggests that the observed dust features in these two galaxies are quite massive ($\gtrsim 10^5 - 10^6$ M$_\odot$) with very large energy requirements if ejected from $z = 0$ ($\gtrsim 10^{52} - 10^{53}$ ergs). Though these dust clouds may be slightly larger (typically 50–100 pc×100–400 pc), their masses are quite similar to the low-$z$ molecular cloud complexes in the inner Milky Way (Dame et al. 1980). We note that for gas column densities like those estimated for these structures ($N_H \gtrsim 10^{21}$), the fraction of hydrogen found in molecular form in diffuse Milky Way disk clouds is $f \sim 25\%$ (Savage et al. 1977). Though we do not fully understand the physical properties of these high-$z$ clouds, if the conditions are not too different than for diffuse material in the disk of the Milky Way, particularly the radiation field, these dusty clouds may contain a significant amount of molecular material. Searches for CO emission from these clouds would be of great interest.

What are the origins of the dusty clouds found at high-$z$ in edge-on spirals such as NGC 891 and NGC 4013? The observed numbers and properties of dust structures seem to be roughly symmetric about the planes of these galaxies, suggesting that they are not associated with warped gas layers. HS97 discuss several mechanisms for expelling dusty material from the thin disks of spirals. Among the more promising of these scenarios are expulsion via (magneto)hydrodynamical flows (Norman & Ikeuchi 1989) and/or radiation pressure (Ferrara 1993). We find that some of the observed dust structures are associated with sites of vigorous star formation in the underlying disk. Indeed some of the morphologies (e.g., shell or cone-like structures) suggest these dust
features may be tracing the expulsion of matter in supernova-driven outflows. Generally we find that such dust structures have closely associated Hα emission. Given the morphologies and associated Hα emission, it is very likely that massive stars and supernovae are playing a role in shaping some of the observed structures. However, most dust structures seem not to have bright associated Hα and their morphologies are less easily associated with the immediate effects of star formation in the disk. Other scenarios must also be considered. For example, it may be possible to form high-z clouds through thermal instabilities in hot extraplanar gas. One of the most significant implications of our images is that whatever processes provide for interstellar thick disk material, the material at high-z in these galaxies must include a significant amount of dust. Thus, if these structures are formed as material is lifted away from the thin disk, the mechanisms responsible for the expulsion cannot be violent enough to destroy the associated dust.

3. High-z Star Formation

In the course of our studies of the dusty ISM at large z-heights, we have identified regions that contain early-type stars far from the thin disks of several edge-on spirals. Fig. 2 shows B-band gray-scale images with Hα contours overlayed for two such regions. In both NGC 891 and NGC 4013 we find unresolved knots of Hα emission at z-heights of 0.6–1 kpc. We tentatively identify these knots of emission as H II regions, though this identification should be confirmed spectroscopically.

In NGC 891, the closer of the two galaxies studied here, we also detect continuum emission in the BVRI bandpasses from several sources associated with Hα emission at |z| > 0.5 kpc. Though our photometry is not yet complete, the high-z continuum sources in NGC 891 seem to require the equivalent of more than 5 main sequence O-stars to produce the observed light. While single early-type stars may be ejected from the thin disk during their lifetimes, most mechanisms for such ejections (e.g., supernova kicks, dynamical ejection from clusters, etc.) seem incapable of explaining groups of stars at such large distances from the midplane. If these regions do indeed contain multiple early-type stars, it suggests that a mode of star formation is operable beyond the thin (inter)stellar disks of spiral galaxies, possibly associated with the massive dust clouds seen in our images.

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References

Bohlin, R.C., Savage, B.D. & Drake, J.F. 1978, ApJ, 224, 132
Dame, T.M., Elmegreen, B.G., Cohen, R.S., & Thaddeus, P. 1986, ApJ, 305, 892
Ferrara, A. 1993, ApJ, 407, 157
Howk, J.C., & Savage, B.D. 1997, AJ, 114, 2463
Norman, C.A., & Ikeuchi, S. 1989, ApJ, 345, 372
Savage, B.D., Drake, J.F., Budich, W., & Bohlin, R.C. 1977, ApJ, 216, 291
Fig. 1: Unsharp-masked views of NGC 891 (top; V-band) and NGC 4013 (bottom; B-band). These images were taken with the WIYN 3.5-m telescope and have seeing-limited resolutions of $0''7$ or $\sim 32$ pc for NGC 891 and $0''6$ or $\sim 50$ pc for NGC 4013). These images show hundreds of absorbing dust structures with heights $0.5 \lesssim z \lesssim 2$ kpc from the midplane. Several dust structures are identified in these images, and the physical properties of these structures are summarized in Table 1. A 1 kpc distance scale is shown on the left side of each image.

Fig. 2: Gray-scale B-band data for NGC 891 (left) and NGC 4013 (right) with H$\alpha$ contours overlayed. Prominent H II regions far above the plane are identified in both galaxies. These H II regions and, in the case of NGC 891, associated continuum sources imply the presence of groups of early-type stars at high-$z$, strongly suggesting that stars may be formed from interstellar thick disk material.
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