Fabry-Perot Imaging Spectroscopy of Starburst and AGN Winds

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Abstract.

To date, the most detailed studies of galactic winds have come from 3-D spectrophotometric observations with radio and Fabry-Perot interferometers. Here, we report the latest results from a long-term optical survey of nearby active and starburst galaxies with the Hawaii Imaging Fabry-Perot Interferometer (HIFI) at Mauna Kea and the TAURUS-2 system in Australia. These data reveal that the outflows are highly complex, highly energetic ($>10^{53}$ ergs in most cases), and the brightest emission often appears to be associated with strong shocks. The outflowing material in the starburst galaxies generally lies on the surface of bubbles or along the walls of funnel-shaped winds rapidly accelerating out of the galactic plane. These winds are sometimes lop-sided and tilted with respect to the polar axis of the host galaxy. Evidence for entrainment of (rotating) disk material is seen in some objects. Our results are combined with HST, radio and X-ray data and discussed in the context of future surveys of distant galaxies on 8-meter class telescopes.

1. Introduction

Active galactic nuclei (AGN) and nuclear starbursts may severely disrupt the gas phase of galaxies through deposition of a large amount of mechanical energy in the centers of galaxies. As a result, a large-scale galactic wind (“superwind”) that encompasses much of the central regions of these galaxies may be created (e.g., Chevalier & Clegg 1985; Schiano 1985). Depending upon the extent of the halo and its density and upon the wind’s mechanical luminosity and duration, the wind may ultimately blow out through the halo and into the intergalactic medium. The effects of these superwinds may be far-reaching. Bregman (1978) has suggested that the Hubble sequence can be understood in terms of a galaxy’s greater ability to sustain winds with increasing bulge-to-disk ratio. Superwinds may affect the thermal and chemical evolution of galaxies by depositing large quantities of hot, metal-enriched material on the outskirts of galaxies. They also offer a natural way to create a cosmically evolving population of large, metal-enriched, kinematically-complex gaseous halos, in many ways resembling the sharp metal lines and Lyman-limit systems observed in quasar spectra.

Strong evidence for spatially-resolved superwinds now exists in several nearby starburst, Seyfert, and dwarf galaxies (e.g., Bland & Tully 1988; Cecil et al. 1990; Heckman et al. 1990; Lehnert & Heckman 1996; Marlowe et al. 1995;
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Meurer et al. 1992; Veilleux et al. 1994; Colbert et al. 1996). Our group is combining Fabry-Perot imaging spectrophotometry with radio and X-ray data to track the energy flow through various gas phases. The complete spatial and kinematic sampling of the Fabry-Perot (FP) data is ideally suited to study the complex and extended morphology of the warm line-emitting material that is entrained in the wind flow. The radio and X-ray data complement the FP data by probing the relativistic and hot gas components, respectively. The high level of sophistication of recent hydrodynamical simulations (e.g., Tomisaka 1990; Slavin & Cox 1992; Mineshige et al. 1993; Suchkov et al. 1994) has provided the theoretical basis to interpret our data and to predict the evolution and eventual resting place (disk, halo, or intergalactic medium) of the outflowing material. In the present paper, we summarize the results on three representative objects from our Fabry-Perot survey and discuss possible implications.

2. The Fabry-Perot Survey

Using the gap-scanning mode of the Hawaii Imaging Fabry-Perot Interferometer (HIFI) on Mauna Kea Observatories and of the TAURUS-2 Fabry-Perot system on the Anglo-Australian Telescope, our group is carrying out a survey of twenty nearby ($z < 0.01$) starburst and Seyfert disk galaxies. Deep tunable-filter images and stare-mode FP spectra supplement some of the data cubes. The objects in our sample were selected on the basis of a priori evidence for large-scale nuclear outflows.

So far, high-quality data cubes have been obtained and analyzed for about a dozen galaxies, and the results have been published for ten of them. Our FP data set allows us to perform spectrophotometric analyses of the line-emitting gas at typically 10,000 – 100,000 positions across the extent of our sample galaxies. These data therefore provide very stringent constraints on the general flow pattern of the line-emitting gas entrained in these outflows.

3. Results

Because of space limitations, we focus our discussion of the results on three of our sample galaxies. These objects were chosen to illustrate the broad diversity of morphologies, kinematics, and energetics associated with galactic winds.

3.1. M82

This prototypical starburst galaxy has long been suspected to host a galactic-scale outflow (e.g., Lynds & Sandage 1963; Burbidge, Burbidge, & Rubin 1964). A recent HST image of this galaxy (Fig. 1) shows the well-known filamentary complex that extends several kpc above and below the disk of M82. The FP data from Shopbell & Bland-Hawthorn (1998) reveal a bipolar outflow of material that originates from the bright starburst regions in the galaxy’s inner disk but is misaligned with respect to the galaxy spin axis. The deprojected outflow velocity indicated by the optical filaments increases with radius from 525 to 655 km s$^{-1}$. Double components are detected in the centers of the outflowing lobes,
Figure 1. Continuum-subtracted Hα+[N II] HST/WFPC2 image of M82 showing dramatic filamentation and bow shock structures in the outflowing lobes. The size of the smallest resolved features in this image is about 2 pc (Shopbell et al. 1999)

with line splitting by $\sim 300$ km s$^{-1}$ over a region almost 1 kpc in size. The lobes lie along an axis tilted by 15$^\circ$ with respect to the spin axis of the galaxy.

The filaments are not simple surfaces of revolution, nor is the emission distributed evenly over the surfaces. These lobes are best modeled as a composite of cylindrical and conical structures, collimated in the inner $\sim 500$ pc but expanding at a larger opening angle of $\sim 25^\circ$ beyond that radius. The wind in M82 therefore seems to be freely flowing into the galaxy halo (“free-wind” phase in the nomenclature of Weaver et al. 1977). Using this outflow geometry and assuming a filling factor of 0.1, Shopbell & Bland-Hawthorn (1998) finds that a kinetic energy of $\sim 2 \times 10^{55}$ is involved in the outflow. There is also some evidence for rotation of the wind filaments about the outflow axis in support of entrainment.

The observed filamentation probably arises from large-scale shocks from the high-speed wind plowing into the gaseous halo and entrained disk material. The line ratios suggest that photoionization by the nuclear starburst play a significant role in the excitation of the optical filament gas, but that shock ionization becomes increasingly important at large radii.
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Figure 2. (left panel) Continuum-subtracted H\(\alpha\)+[N II] HST/WFPC2 image of the nuclear bubble in NGC 3079. The spatial resolution is about 8 pc. (upper right panels) Results of numerical simulations from Suchkov et al. (1994). Note the resemblance with the fine structures observed in the HST image. (lower right panel) A view of the star-forming disk in NGC 3079 derived from the HST images. Elevated line-emitting chimneys and filaments are seen near the brightest H II regions. (Cecil et al. 1999)

3.2. NGC 3079

In no other galaxy is the impact of superwinds more evident than in NGC 3079, a nearby edge-on spiral galaxy which is host to a spectacular kpc-scale bubble (see Fig. 2). Violent gas motions that range over 2,000 km s\(^{-1}\) are detected across the bubble and diametrically opposite on the other side of the nucleus. The unusual gaseous excitation (e.g., [N II] \(\lambda 6583\)/H\(\alpha\) > 1) of the line-emitting gas in the bubble region confirms that shocks are important.

This is the most powerful example known of a windblown bubble (\(~ 2 \times 10^{56} \, N_e^{-1}\) ), and an excellent laboratory to study wind dynamics. An ovoidal bubble, inflated from the nucleus with monotonically increasing velocities (\(V \propto R^n\) with \(2 < n < 3\)) and inclined \(~3^\circ\) from the plane of the sky, provides a good first-order fit to the observed velocity field. The dimensions and energies of the bubble imply that it is in the blowout phase and partially ruptured. A detailed dynamical analysis of this outflow indicates that the wind alone can contribute up to \(5t_{\text{outflow,8}}\%\) of the total metal content of the host galaxy, where \(t_{\text{outflow,8}}\) is the outflow lifetime in units of \(10^8\) yr (Veilleux et al. 1994).

The core of NGC 3079 harbors both a nuclear starburst and an AGN. The nature of the energy source that drives the outflow is not clear at present. The poorly constrained electron density and filling factor of the warm line-emitting
material in the bubble are the main sources of uncertainty in the calculation of the energetics. To shed new light on this issue, we recently obtained a WFPC2 HST image of NGC 3079 with resolution of \( \sim 0.1 \) (\( \sim 8 \) pc; Fig 2). The HST image reveals intricate patterns in the line-emitting material near the top of the bubble. These features share a remarkable resemblance with those observed in hydrodynamical simulations (e.g., Suchkov et al. 1994) – they are probably the signatures of Rayleigh-Taylor instabilities in the entrained material. Similar filamentary structures are observed near the brightest star-forming regions in the disk of NGC 3079, bringing further support to the idea of a dynamically active disk in this galaxy (Veilleux et al. 1995). A preliminary quantitative analysis of the HST data suggests that the AGN in NGC 3079 is not contributing significantly to the nuclear outflow.

### 3.3. Circinus

The FP data on Circinus show a complex of ionized filaments extending radially from the nucleus out to distances of 1 kpc (Fig. 3). The velocity field of the filaments confirms that they represent material expelled from the nucleus or entrained in a wide-angle wind roughly aligned with the polar axis of the galaxy. Extrapolation of these filaments to smaller radii comes to within 1" of the active galactic nucleus, therefore suggesting a AGN or nuclear starburst origin to these features. The outflow involves a fairly modest kinetic energy (\( \sim 10^{53} N_{e,2}^{-1} \) ergs) and therefore appears to lie at the low energy end of the distribution for wide-angle events observed in nearby galaxies.

The complex of radial filaments and bow shocks detected in the Circinus galaxy is unique among active galaxies and does not fit within the standard evolutionary picture of windblown bubbles (e.g., Weaver et al. 1977). It is not clear at present why that is the case. The discovery of these features in the Circinus galaxy, a spiral galaxy with an abnormal richness of gas (Freeman et al. 1977), brings up the possibility that we may be witnessing a common evolutionary phase in the lives of gas-rich active galaxies during which the dusty cocoon surrounding the nucleus is expelled by the combined action of jet and wind phenomena.

### 4. Future Avenues of Research

The overall agreement between the simulations of Suchkov et al. (1994) and current observations of local galaxies with galactic winds augurs well for the future. However, substantial quantitative differences still remain: e.g., current models severely underestimate the outflow velocities of the entrained line-emitting material (by more than an order of magnitude in NGC 3079). A more realistic treatment of the multi-phase ISM in the host galaxy may help solve some of these problems and may help explain the morphological peculiarities of the outflow in the gas-rich galaxy Circinus.

The results from these observational and theoretical studies will eventually serve as a critical local baseline for future deeper surveys with IFUs on 8-meter class telescopes from the ground and in space. Current surveys suggest that galaxies have experienced a very active phase of star formation and nuclear activity around redshifts of 1-3 (e.g., Madau, Pozzetti, & Dickinson 1998;
Figure 3. Line flux images of Circinus, the nearest Seyfert galaxy: a, [O III] λ5007 and b, blueshifted Hα. The position of the infrared nucleus is indicated in each image by a cross. The spatial scale, indicated by a horizontal bar at the bottom of the [O III] image, corresponds to ~ 25 arcsec or 500 pc. Note the unusual complex of radial filaments emerging from the nucleus. PA_{major}(disk) = 30°, i(disk) = 65° (Veilleux & Bland-Hawthorn 1997)

Schmidt, Schneider, & Gunn 1995). Detailed comparisons of high-redshift galaxies with local superwind hosts and with state-of-the-art numerical simulations of windblown bubbles will help us quantify the impact starburst- and AGN-driven winds may have had on the chemical and thermal evolution of the galactic and intergalactic environments.

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