MOLECULAR GAS AND NUCLEAR OUTFLOWS

JUDITH A. IRWIN
Queen's University
Dept. of Physics, Kingston, Ontario, Canada, K7L 3N6

1. Introduction

There is now overwhelming evidence that spiral galaxies can experience nuclear outflows, from radio lobes perpendicular to the disks of edge-on galaxies (Hummel et al. 1983), to optical ionization cones (see list in Wilson and Tsvetanov 1994), to spectacular X-ray emission extending many kpc beyond the disk (e.g. Dahlem et al. 1996). These observations indicate that hot and/or energetic components of the ISM can escape away from the plane of the galaxy from their origin in the nuclear vicinity.

Less obvious, however, is whether the cool components of the ISM, i.e. the neutral atomic and molecular gas, can also participate in the outflows. If so, observations in their tracers, notably HI and CO, can have significant benefits over observations of their energetic counterparts. Firstly, the spectral line data can provide information on the velocity field and, ultimately, the energetics of the outflow. Secondly, unlike the optical, these lines do not suffer from obscuration, allowing one to peer into the nuclear vicinity itself. The latter point is particularly important for edge-on galaxies which are most suited for detecting outflows in the first place.

2. HI Outflows

A good *resolved* example of an HI outflow is NGC 1808 (Koribalski et al. 1993). In addition to very wide lines in the nucleus, subtraction of a model velocity field for this galaxy results in residuals which show a discrete negative velocity feature along the minor axis. An outflow velocity > 150 km s^{-1} is implied. This outflow does not probe the nuclear region itself, however, since it is observed over scales of several kpc.

Nuclear HI is often seen in absorption which can be advantageous for identifying outflows. However, structure in the background (unresolved) continuum can make interpretation difficult, and determining the HI mass

Y. Sofue (ed.), The Central Regions of the Galaxy and Galaxies, 213-214.

also requires a knowledge of the gas spin temperature. More problematic is that there is often little HI in spiral galaxy nuclei. Thus, molecular gas, which is often abundant, may be a better tracer.

3. CO Outflows

Molecular gas has been widely discussed elsewhere in its capacity as providing fuel for nuclear activity and also in focussing outflows. In terms of being *affected* by the outflow, there are a few examples, with NGC 3628 (a starburst) and NGC 3079 (an AGN) being most illustrative.

NGC 3628 (Irwin and Sofue 1996) is an interacting galaxy with an outflow region in the form of a northwards opening "velocity cone" and southern extensions to a z height of > 400 pc. The most obvious CO outflow is at the presumed origin of kpc scale perpendicular Hα filaments. Also at this position is the best defined of several expanding molecular shells, the largest of which has an expansion kinetic energy $> 2.5\ 10^{54}$ ergs. Though the shells span a range of size, all kinematic timescales are a few 10^6 yr, thus dating the starburst.

NGC 3079 (Irwin and Sofue 1992) has kpc-scale radio lobes which originate in a compact VLBI core. There is a large amount of molecular gas in the nuclear region (of order 10^{10} $M_\odot$) and within the nuclear molecular disk is an embedded "tilted component". The tilted component is aligned with the nuclear VLBI jet and has been interpreted as a molecular outflow. The kinetic energy of the outflow is uncertain because most velocities appear to be in the plane of the sky, but is at least 10^{54} ergs. The jet energy is sufficient to supply this minimum.

4. Summary

In some galaxies, molecular gas appears to participate in nuclear outflows and provides a potentially important diagnostic for interpreting these flows. The loss of molecular gas mass from the active region could be significant and should be considered in the context of starburst or AGN models.

References

Dahlem, M., Heckman, T. M., Fabbiano, G., Lehnert, M. D., and Gilmore, D. (1996) *The Astrophysical Journal*, **461**, 724.

Hummel, E., van Gorkom, J. H., and Kotanyi, C. G. (1983) *The Astrophysical Journal*, **267**, L5.

Irwin, J. A., and Sofue, Y. (1992) *The Astrophysical Journal*, **396**, L75

Irwin, J. A., and Sofue, Y. (1996) *The Astrophysical Journal*, **464**, 738.

Koribalski, B., Dahlem, M., Mebold, U., and Brinks, E. (1993) *Astronomy and Astrophysics*, **268**, 14.

Wilson, A. S., and Tsvetanov, Z. I. (1994) *The Astronomical Journal*, **107**, 1227.