ON THE DYNAMICS OF THE BROAD-LINE GAS IN SEYFERT 1 GALAXIES

JOEL E. TOHLINE
Theoretical Division, Los Alamos National Laboratory

AND

DONALD E. OSTERBROCK
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz

Received 1981 August 24; accepted 1981 September 25

ABSTRACT

Recent analyses of the properties of nearby Seyfert 1 galaxies indicate that there is no correlation between the widths of the broad permitted lines and the observed inclination of the galaxies' spiral disks. The absence of such a correlation suggests that the lines are not rotationally broadened. We point out in this Letter, however, that there are both observational and theoretical grounds for believing that rapidly rotating gas in the nucleus of a spiral galaxy need not be confined to the same plane as the galaxy's primary disk. Therefore, the absence of a correlation between line widths and disk inclination does not rule out rotation as the primary broadening mechanism for lines emitted from the broad-line gas in Seyfert 1 galaxies. Models of the dynamics of the nuclear gas in active galactic nuclei should allow for a possible "tilted" orientation of the gas.

Subject headings: galaxies: internal motions — galaxies: nuclei — galaxies: Seyfert

I. INTRODUCTION

The broad permitted lines observed in the spectra of Seyfert 1 galaxies are believed to arise from a dense plasma that is confined to their central nuclear regions. The nature of the velocity field that produces the observed line broadening in the central regions of these galaxies remains a puzzle. The dimensions of the broad-line regions, as estimated from the luminosity in the emission lines and also from the time scales of observed spectral variations, are very small—of order 1 pc or less. So, even in the nearest Seyfert galaxies there is little hope for direct spatial resolution of the Doppler measurements. The overall shape and the detailed structure of the profiles of the broad lines should, however, provide a great deal of information regarding the velocity field of the broad-line gas. An atlas of observed profiles is now being prepared for publication (Osterbrock and Shuder 1982) which should be helpful for comparison with theoretical models of the dynamics of the broad-line gas.

To explain the extreme velocity widths of the broad lines in Seyfert 1 galaxies, Woltjer (1959) suggested that the plasma from which the lines are emitted is rapidly rotating. This explanation has probably been less widely accepted than the alternate working hypothesis of largely radial outflow from the nucleus (e.g., Burbidge, Burbidge, and Sandage 1963; Blumenthal and Mathews 1979), but it has recently received renewed support. Shields (1977) and Osterbrock (1978) have reemphasized that although the dimensions of the broad-line region are extremely small, rotation can be the broadening mechanism for the lines if the gas is orbiting a supermassive object at the galaxy's center. Assuming that the gas is rotationally broadened, and realizing that the vast majority of Seyfert nuclei are located in the center of spiral galaxies (see Adams 1977, and references cited therein), it is natural to assume that the angular momentum vector of the broad-line gas is in the same direction as that of the surrounding spiral disk. Under this assumption, the observed widths of the permitted lines in Seyfert 1 galaxies would be expected to show a correlation with their apparent axial ratios, i.e., with the observed inclinations of the spiral disks that surround Seyfert nuclei. Face-on galaxies should, on the average, exhibit narrower line widths than edge-on galaxies. Keel (1980) and Simkin, Su, and Schwarz (1980) have studied the available observational data on nearby Seyferts and have found no such correlation. One might conclude, therefore, that, in general, rotation is not responsible for the broadening of the permitted lines. We point out in this Letter, however, that such a conclusion is not justified. There are both observational and theoretical reasons for thinking that the gas in the nucleus of a spiral galaxy need not be orbiting in the same plane as gas in the galaxy's primary spiral disk. Therefore, a correlation between line widths and disk inclination is not expected, even if the permitted lines in Seyfert 1 galaxies are rotationally broadened.

1Lick Observatory Bulletin, No. 903.
II. OBSERVATIONS OF TILTED NUCLEAR DISKS

There is observational evidence that, in at least two “normal” galaxies, nuclear gas is rotating about an axis that is different from the axis of the primary spiral disk. Far-infrared measurements by Lacy et al. (1979) of the [Ne II] $\lambda$12.8 $\mu$m line show that gas in the central 1 pc of our Galaxy appears to be rotating about an axis that is nearly perpendicular to the symmetry axis of the Galaxy’s disk. If the volume over which the measurements are taken is extended out to a diameter of 1.5 pc, the spin axis of the nuclear gas shifts about 30° toward the axis of symmetry of the disk, that is, it is still inclined by about 60° to this axis. These measurements have been confirmed by Nadeau, Neugebauer, and Matthews (1981), who have measured the Br$\gamma$ line emission from the Galaxy’s nuclear gas. On a much larger scale, Burton and Liszt (1978) found evidence from H I $\lambda$21 cm measurements that the gas within 1.5 kpc of the center of our Galaxy lies in a plane whose axis of rotation is tipped by 22° with respect to the axis of symmetry of the Galaxy’s primary disk. They confirmed this result with measurements of the CO $\lambda$2.6 mm emission line (Liszt and Burton 1978). Other galaxies cannot be observed with nearly the same spatial resolution as our own Galaxy, so the dynamics of their nuclear gas is more difficult to determine observationally. However, the most direct interpretation of the velocity field of the fairly normal spiral NGC 3672 indicates that the rotation of its nuclear gas makes a large angle—close to 90°—with the rotation axis of its primary disk (Rubin, Thonnard, and Ford 1977).

As Rubin, Thonnard, and Ford (1977) point out, the amount of gas in the nucleus of NGC 3672 is quite small. This is generally true for the nuclei of normal spirals and is true for the ionized gas in the broad-line regions of Seyfert 1 galaxies. If this gas is being fed in from mass loss by stars, from the debris of star-star collisions, or from intergalactic matter, it is clear that at a given instant in time its angular momentum vector would not necessarily be aligned with the spin axis of the spiral disk. This physical explanation of the tilted nuclear disk in NGC 3672 and in our Galaxy suggests that such disks are transient. In the following section we discuss a model that can explain orthogonally oriented gas disks in galaxies as a steady-state phenomenon. This model leads us to suggest that tilted disks similar to those seen in NGC 3672 and in our Galaxy may be relatively common features of spiral galaxies and, particularly, of Seyfert galaxies.

III. TUMBLING, BARLIKE POTENTIAL WELLS

The shape of the gravitational potential well of most galaxies is defined to a large extent by a dominant stellar component. Particles of gas in most galaxies, therefore, move as massless test particles in the potential well defined by a distribution of stars. Dissipative processes in the gas generally cause it to settle into a disk, and furthermore, as is discussed in detail by Tohline, Simonson, and Caldwell (1982), if the stars define a spheroidal structure, the differential precession of gas particle orbits coupled with dissipation will align the disk with the equatorial plane of the spheroid. The time scale in which gas settles to the equatorial plane of the spheroid is estimated to be comparable to the nodal precession rate $\tau_{np}$ of particle orbits:

$$\tau_{np} \sim \frac{2\pi}{\omega_0 J_z} \sim 10^7 \text{yr} \left( \frac{R_{\text{kpc}}}{1000}\right) \left( \frac{v_{1000}}{\text{km} \text{s}^{-1}} \right)^{-1},$$  

where $\omega_0$ is the orbital angular velocity of a gas particle, and $J_z$ is the absolute value of the quadrupole moment of the spheroidal potential well; $R_{\text{kpc}}$ is the particle’s orbital radius in kpc, and $v_{1000}$ is its orbital velocity in units of 1000 km s$^{-1}$. Extending the work of Tohline, Simonson, and Caldwell (1982), Tohline and Durisen (1982, hereafter TD) have analyzed how gas will settle into a prolate spheroidal galaxy—a stellar “bar,” if you will—if the spheroidal potential well is not stationary in time but is instead tumbling end over end. (Galaxy models calculated by Miller [1978] and by Miller and Smith [1979a, b] have evolved into tumbling structures of this sort.) TD have found that the plane to which gas will settle in a tumbling bar potential is not the same at all radii. Generally, at large distances from the center of the potential well, gas will settle into a plane so that the angular momentum vector of the gas is aligned with the tumble axis of the bar; TD call this the inertial equatorial plane (see Fig. 1). However, gas in the central region of a tumbling prolate potential well may in many instances settle into the bar equatorial plane (Fig. 1), which is oriented orthogonally to the outer disk. The angular momentum vector of the gas in this inner region aligns with the major axis of the bar. The radius at which the “preferred plane” for the gas changes orientation is given approximately by the radius at which $\tau_{np}$ (Eq. [1]) equals the tumble period of the bar $\tau_t$. The inner disk may not exist at all if a rapidly tumbling spheroid is only weakly prolate, but its radius may be comparable to the radius of corotation $R_{\text{CR}}$ ($R_{\text{CR}} \equiv$ radius at which the orbital period of the gas equals $\tau_f$) if the quadrupole moment of the bar is large.

TD have suggested that the peculiar galaxy NGC 2685 (see Plate 7 of Sandage 1961) is the best evidence to date for the existence of orthogonally oriented disks in a single, barlike galaxy. Careful observations of elliptical galaxies with prolate structures (Bertola and Galletta 1978; Hawarden et al. 1981; Tohline, Simonson, and Caldwell 1982) may reveal additional evidence of this type of structure. What is particularly relevant to the subject of this Letter, however, is the connection between the model analyzed by TD and
barred spiral galaxies. Huntley (1980) and Peterson and Huntley (1980) have used a tumbling stellar bar in gas dynamic simulations to drive spiral structure in a disk and have successfully reproduced a variety of kinematic features observed in barred spiral galaxies. Their simulations confined the gas to the inertial equatorial plane of the system and, therefore, did not allow for the possible existence of an inner orthogonal disk. Guided by the evidence that a tumbling bar can drive realistic barred spiral structure in a disk, TD have suggested that many barred spiral galaxies should in fact possess small central disks that are oriented in a direction orthogonal to the primary disks of the galaxies (see, however, the provisional remarks made by TD). To our knowledge, the central regions of barred spirals have not been searched for the existence of such structures. We should note, however, that, for a tumble period \( \tau \sim \text{few} \times 10^8 \) yr that is characteristic of the pattern speeds used to model barred spiral galaxies and for a relatively weak bar \((|J_2| \ll 0.01)\), the inner disk may be only a fraction of 1 kpc in size. So it is perhaps understandable that inner orthogonal disks in barred spiral galaxies are not readily detected on optical photographs.

Neither NGC 3672 nor our Galaxy is obviously barred. However, the following variation on the TD model may explain the existence of tilted nuclear disks in galaxies that are not obviously barred. To first order, the tidal forces that are imposed on a spiral galaxy's disk by a passing or orbiting companion generate a perturbation in the disk's gravitational potential well that is like the tumbling, prolate spheroidal potential analyzed by TD. Therefore, tidal encounters may also cause gas in the nuclear region of a galaxy to settle toward a plane that is different from the galaxy's traditional equatorial plane. As in the TD model, the relative size of this central tilted disk region will depend on the radial structure of the galaxy's own potential well and on the strength of the quadrupole component of the tidal field.

IV. GAS IN THE CENTRAL REGION OF SEYFERT 1 GALAXIES

Morphological studies of Seyfert galaxies by Adams (1977), Simkin, Su, and Schwarz (1980), and Su and Simkin (1980) show that a large fraction of the galaxies either barred spirals or have close companions. Drawing on the theoretical model discussed in § III, then, there is reason to believe that in many Seyfert 1 galaxies the angular momentum vector of the broad-line nuclear gas does not point in the same direction as the angular momentum of the primary spiral disk. More precisely, broad-line gas that settles into the bar equatorial plane (Fig. 1) will align its angular momentum vector with the major axis of the perturbing bar. Therefore, if rotation is the primary mechanism by which the permitted lines in the spectrum of a Seyfert 1 galaxy are broadened, we do not expect the widths of these lines to correlate with the observed inclination of the galaxy's spiral disk. In the future, models of the dynamics of the nuclear gas in active galactic nuclei should allow for the possible "tilted" orientation of the gas.

We are grateful to J. S. Miller, J. M. Shuder, R. H. Durisen, R. D. Cohen, and W. C. Keel for many helpful discussions on these points, as well as to M.
REFERENCES


Donald E. Osterbrock: Lick Observatory, University of California, Santa Cruz, CA 95064

Joel E. Tohline: Group T-6, MS 288, Los Alamos National Laboratory, University of California, P.O. Box 1663, Los Alamos, NM 87545