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VERTICAL SHEAR OF THE GALACTIC INTERSTELLAR MEDIUM

Robert A. Benjamin

Department of Physics, University of Wisconsin-Madison, USA

RESUMEN

La detección de absorción en UV, 21 cm, Hα y otras líneas difusas de emisión en el óptico de gas de hasta 10 kpc sobre el plano de la Vía Láctea y de otras galaxias, permite estudiar la rotación de las "atmósferas" ionizadas de las galaxias. Esta rotación tiene implicaciones al entendimiento del potencial gravitacional Galáctico, al transporte del momento angular del disco y al mantenimiento del dinamo Galáctico. Las evidencias indican que el gas rota de forma casi cilíndrica hasta varios kiloparsecs. Esto va en contra de la idea de que, suponiendo un modelo de masa razonable para la Galaxia, debía de haber un gradiente de rotación pronunciado como función de la altura sobre el plano. Por ejemplo, en el corte vertical a un radio galactocéntrico de $R = 5$ kpc en NGC 891 hecho por Rand, la velocidad de rotación baja ~ 30 km s^{-1} de $z = 1$ a 5 kpc y debía bajar unos 80 km s^{-1}. La tensión magnética puede resolver la discrepancia y se examinarán otras posibilidades en el futuro.

ABSTRACT

The detection of UV absorption, 21 cm, Hα and other diffuse optical emission lines from gas up to ten kiloparsecs above the plane of the Milky Way and other galaxies provides the first opportunity to probe the rotational properties of the ionized "atmospheres" of galaxies. This rotation has implications for our understanding of the Galactic gravitational potential, angular momentum transport in the Galactic disk, and the maintenance of a Galactic dynamo. The available evidence indicates that gas rotates nearly cylindrically up to a few kiloparsecs. This is in contrast to the expectation that there should be a significant gradient in rotation speed as a function of height assuming a reasonable mass model for the Galaxy. For example, for a vertical cut at galactocentric radius $R = 5$ kpc in NGC 891 by Rand, the rotation speed is observed to drop by ~ 30 km s^{-1} from $z = 1$ to 5 kpc and is expected to drop by 80 km s^{-1}. Magnetic tension forces may resolve this discrepancy. Other possiblilities will be examined in the near future.

Key Words: **HYDRODYNAMICS — ISM: GENERAL**

1. HOW *DOES* EXTRAPLANAR GAS ROTATE?

Over the past two decades it has become clear that galaxies have extended ionized atmospheres. What factors determine the kinematics of this gas? The rotation curves of neutral gas have been a valuable probe for the dynamics of galaxies, and Bland-Hawthorn, Freeman, & Quinn (1997) have begun to address how Hα rotation curves may extend radially beyond the H I. Here, we ask the complementary question: How do rotation curves extend vertically?

We start with an overly brief summary of the observations. Currently there are data for two "normal" galaxies: the Galaxy and NGC 891.[1] In our Galaxy, the neutral hydrogen has a component with scaleheight ~ 500 pc, which is observed to corotate (Dickey & Lockman 1990). UV absorption lines of Si IV and C IV

[1] Extraplanar emisison has also been seen up to 11.6 kpc above the plane in the starburst galaxy M82 (Lehnert, Heckman, & Weaver 1999) and up to 4 kpc in the Virgo cluster Seyfert galaxy NGC 4388 (Veilleux et al. 1999).

are found to have a scaleheight of 3 kpc; line profiles show little deviation from cylindrical rotation up to this height (Savage, Sembach, & Lu 1997), except for lines of sight towards the inner Galaxy (Tripp, Sembach, & Savage 1993). However, for all Galactic studies, there is always that possibility that some of the measured velocities consists of vertical rather than rotational motion.

This difficulty can be circumvented by looking at edge-on spirals. This has been done for NGC 891 which has one long-slit spectrum perpendicular to the plane of the Galaxy at $R = 5$ kpc that traces the kinematics of Hα, [N II], and [S II] up to five kiloparsecs off the plane (Rand 1996). Below $z \cong 1$ kpc, dust extinction in the disk does not allow one to sample the full path through the disk. However, from $z = 1$ kpc to 5 kpc, the rotation speed drops by 30 km s^{-1}. Although this is a significant drop, it is not as much as is expected in the models we will examine. There is also 21 cm data extending up to ~ 3 kpc over much of the Galaxy (Swaters, Sancisi, & van der Hulst 1997). Exterior to $R \cong 7$ kpc, a strip averaged between $2.8 > z > 1.4$ kpc shows a rotation speed that is ~ 25 km s^{-1} lower than the value in the plane. Swaters et al. have shown that this drop in rotation speed is unlikely to be due to flares or warps. Interior to $R \cong 7$ kpc, the difference is much greater, reaching 100 km s^{-1} at $R = 5$ kpc. However, this is inconsistent with the Hα data. This drop may therefore be due to a deficit of extraplanar neutral gas interior to $R \sim 7$ kpc, rather than a decrease in rotation speed. This discrepancy highlights the principal weakness in using edge-on systems as a probe for rotational parameters: one must have a reasonable model for the radial and vertical density distribution of the emitting gas.

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2. HOW *SHOULD* EXTRAPLANAR GAS ROTATE?

To answer this question, it is first necessary to adopt a model for the interstellar medium as a whole. Is the extra-planar ISM a collection of dense "clouds" which zip around the Galaxy like stars, with modification to include drag and cloud-cloud collisions? Do we imagine it as a continuum fluid disk in radial and vertical hydrostatic equilibrium? Or do we imagine it as something in between, with parts of the interstellar medium in equilibrium, disturbed in spots by supernova explosions resulting in extraplanar gas being ejected quasi-ballistically into the halo? Examples of all of these points of view exist in the astrophysical literature, and to date there has been no compelling reason to conclusively rule out any of these pictures. Nevertheless, to make progress, we must adopt one.

For the purpose of this proceeding, we model the extraplanar gas as a hydrostatic continuum fluid disk. The steady-state equation of motion for a fluid element above the disk is given by solving the momentum equation:

$$\nabla\Phi - \frac{v_{obs}^2}{R}\hat{\mathbf{R}} + \frac{1}{\rho}\nabla p + \frac{1}{4\pi\rho}(B\cdot\nabla)B + f_{visc} + f_{boundary} = 0. \tag{1}$$

In this equation, the terms from left to right indicate the effects of the gravitational potential (Φ), the actual rotation at radius R (v_{obs}), the pressure gradient (∇p, which will implicitly include magnetic and cosmic ray pressures), the tension of the magnetic field (B), a viscous term, and the boundary effects. For this proceedings and because of lack of knowledge, we will neglect the effects of the turbulent viscosity term and ram pressure term. We now consider the remaining terms.

Gravity: We use, and highly recommend, the gravitational potential model of Dehnen & Binney (1998), which consists of a superposition of disks and spheroids. There are several models, each optimized to fit several data sets constraining the Galactic mass distribution. The "predicted" velocity is then the rotation velocity which balances the radial component of gravity with rotation: $v_{pred} = \sqrt{R(\partial\phi/\partial R)}$. As the height increases, the radial component of gravity decreases and the predicted rotation velocity decreases. This effect is more pronounced at smaller Galactocentric radius. At $R = 5$ kpc, the rotation velocity drops by 80 km s^{-1} from $z = 1$ to 5 kpc, while at $R = 8$ kpc, the rotation velocity drops by 50 km s^{-1}. This is much greater than observed. *All* of the mass models of Dehnen & Binney, including the ones with significantly flattened dark matter halos, yield similar results. Most of the drop off is due to geometrical projection effects.

Pressure gradient: If one assumes that the pressure is a function of density only, $p = p(\rho)$, the radial and vertical components of the momentum equation are

$$\frac{\partial}{\partial z}(G(\rho) + \Phi) = 0\ , \qquad \frac{\partial}{\partial R}(G(\rho) + \Phi) = \frac{v^2}{R}, \tag{2}$$

where $G(\rho) = \int (1/\rho)(dp/d\rho)\, d\rho$. Since the first equation shows $(G(\rho) + \Phi)$ is independent of z, the velocity in the second equation is also independent of z (York et al. 1982). This is a general result and leads to the expectation that all fluids in a gravitational field should rotate cylindrically. In this case, since the gravitational potential term is decreasing steeply with height, it implies an inward directed force due to the pressure gradient, i.e., a low pressure hole over the center of the Galaxy. This seems ruled out on observational grounds. First, Snowden et al. (1998) has shown the presence of high pressure hot interstellar bulge with a radial scalelength of a few kiloparsecs . Second, observations of the synchrotron halo of the Galaxy have been used to construct models of the combination of the cosmic ray and magnetic pressure which also indicate high pressures at smaller radii (Ferriere 1998). Using this second model including a hot halo from Pietz et al. (1998), the net effect of the pressure gradient is to *decrease* the rotation speed by 5–20 km s^{-1}. Thus, the incorporation of the pressure gradient term worsens the discrepancy between the predicted and observed rotation velocity.

Magnetic tension: Whereas a reasonable amount of data constrains the gravitational potential and pressure gradients for Galaxy, there is little information regarding the geometry and strength of the Galactic magnetic field. This is unfortunate since magnetic fields almost certainly play a significant role in the ionized extraplanar gas. The role of magnetic pressure gradients, $\partial(B^2/8\pi)/\partial R$ was implicitly included in the the pressure gradient. However, if the fields are curved, the tension in the field results in a force directed radially inward with a strength proportional to the local radius of curvature. The force is v_A^2/r_{cur}, where the Alfven speed is given by $v_A = 18.6\,\mathrm{km\ s^{-1}} B_{\mu G} n_{-2}^{0.5}$. The momentum equation reduces to

$$v_{obs}^2 - v_{pred}^2 = \frac{R}{r_{cur}} v_A^2. \tag{3}$$

For a halo field of $B = 1\mu$G independent of z and a density structure for the gas of $n_{-2} = 2.5e^{-z/0.9\mathrm{kpc}}$, the difference between the observed and predicted velocity yields the field curvature at (z, R). For example, at $(z, R) = (2\,\mathrm{kpc}, 8\,\mathrm{kpc})$, we find $v_{pred} = 200\,\mathrm{km\ s^{-1}}$, $v_{obs} = 220\,\mathrm{km\ s^{-1}}$, and $v_A = 34\,\mathrm{km\ s^{-1}}$, yielding a radius of curvature of $r_{cur} = 1\,\mathrm{kpc}$. This is not an unreasonable value, and is reminiscent of the vertical tension force needed by Boulares & Cox (1990) to explain the vertical hydrostatic equilibrium of the galactic ISM. It is also supported by observations of large scale Hα filaments (Haffner, Reynolds, & Tufte 1998).

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Robert A. Benjamin: Physics Dept., University of Wisconsin-Madison, 1150 University Ave., Madison, WI 53711, USA (benjamin@wisp.physics.wisc.edu).