80. ON THE CIRCULATION OF GAS NEAR THE GALACTIC CENTER

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Abstract. A model of a quasi-steady circulation of gas near the galactic center is considered to explain the outward motion of the 3-kpc arm. A hydromagnetic wind from the galactic nucleus reaches the 3-kpc arm, where a shock is formed; then the gas moves out of the plane and eventually returns to the nucleus. The secular behavior of the model is discussed.

In a discussion of the spiral structure of our galaxy it is natural to inquire briefly into the origin of the striking outward motion of the 3-kpc arm. The first question that one might ask is whether the observed motion represents an outward swing of the gas which has a large oscillating radial component of velocity. In this case, if the 3-kpc arm represents the compressional phase of a wave motion, we might expect that at some galactic longitudes, gas should be falling toward the galactic nucleus. Certainly, this possibility is difficult to rule out observationally, but the situation should be highly dissipative since the flow must have a large component normal to the wave, and it is difficult to imagine what might maintain such large radial motions. Nevertheless, this is a possibility that remains open.

The other possible source of the radial motions that has been widely considered is a flow from the galactic center. Here again, opinion is divided on the time dependence of the flow. One school of thought postulates an explosion in the galactic center as the cause of the outflow, while the other possibility that has been considered is a quasi-steady wind from the galactic center. Both points of view have their difficulties, and I shall not attempt to summarize them here. Certainly the two possibilities need further discussion, and definite models are required for the purpose. Here, I wish to outline a possible model for a steady flux of gas from the galactic center.

The simplest possible case is an axisymmetric, steady flow, of an isothermal, nonturbulent gas, with no magnetic fields. It is then straightforward to treat a disk-like outflow of this kind from the galactic center (Moore and Spiegel, 1968) if it is further assumed that the gravitational field is specified. The discussion is much like that of the solar wind and the solution which is most compatible with observations accelerates through a sonic point, producing large radial motion. This radial motion is arrested by a rather complicated shock (or compressible hydraulic jump) which ionizes the gas and lifts much of it from the galactic plane. If it may be supposed that the gas that leaves the plane rains back into the galactic center the difficulty of a source of mass for the flow is alleviated. It is also tempting to associate the shock with the 3-kpc arm.

The model described has two serious deficiencies. First, it does not provide a cause for the outflow so that the flow is effectively taken as an initial condition. Second, it

Becker and Contopoulos (eds.), The Spiral Structure of Our Galaxy, 441–443. *All Rights Reserved.*

leads to angular-momentum conservation, hence to $v \propto r^{-1}$, where v is the azimuthal velocity component and r is the distance from the galactic center. This result is not compatible with the observed rotation law. To remove these deficiencies we might try to introduce a nonradial force, and a magnetic field seems to be suitable for this purpose (Moore and Spiegel, 1966).

Mestel, Moore, and I have recently re-examined the picture of a hydromagnetic wind from the galactic center, adding to the above-listed assumptions that the gas is cold. We have also adopted the artifice of a cylindrical geometry. In that case the governing equations can be solved completely as is known from numerous works on stellar wind theory and galactic hydromagnetics (Woltjer, 1965). In this model we have not included a gravitational z-force and we have assumed for simplicity a monotonic variation of gravitational potential with distance from the axis of rotation. We further assume the existence of a central gaseous object which is relatively massive (say 10^8 $M_\odot$) and fairly compact (tens of parsec). The model is encouraging in two respects.

First, there is the conclusion that gas just at the edge of the central object, rotating with it, but with no radial velocity, is accelerated outward. This outward acceleration arises from the tendency of a poloidal field to cause the gas to corotate with the central body. Thus, the gas will rotate more rapidly than the circular velocity so that its centrifugal force surpasses the gravitational force. We conclude then that a moderately strong poloidal field near the galactic center ($\lesssim 10^{-4}$ G) drives a moderately strong wind from the galactic center. Unfortunately, there are several parameters in the problem (the angular velocity of the central object, the magnetic flux, the mass flux, and the energy of the flow) in addition to those of the gravitational field, so that many solutions are possible. The type that seems preferable gives a continued radial acceleration which, at a certain distance outward, becomes infinite, and we anticipate a shock wave, much as in the nonmagnetic case. This shock would inhibit outflow beyond it, so that the flow is largely decoupled from that in the outer galaxy. In a disk-like flow of this kind, we believe that material could again return to the central object, and that the magnetic field lines would also reconnect in this way.

The second interesting consequence of the model is that the rotation curve of the gas resembles the observed one near the galactic center, irrespective of the details of the mass distribution. For the solution we have outlined, with increasing r, the rotational velocity rises to a maximum, drops to a relative minimum, and then rises again for a short distance, where it then reaches the singular acceleration just mentioned. The locations of the maximum and the minimum depend on the unknown parameters mentioned above, so that in this model, the rotation curve cannot be used to infer the mass distribution in the central regions of the galaxy.

We conclude therefore, that a moderately strong field near the galactic center leads us to expect a flow from the galactic center and such a flow would seem to be a good candidate for the cause of the radial motion of the 3-kpc arm. Indeed, I feel that the shock in the outflow should be associated with the arm. On the other hand, I must stress that the study of such models is far from complete. All the ways we have considered of reconnecting the field lines produce magnetic neutral points. Thus, we have to expect instabilities in the model, perhaps of an explosive kind. Other instabilities must be investigated as well, such as non-axisymmetric gravitational stabilities.

A crucial unsolved problem is the secular behavior of the model. Radiative losses in the shock require an energy source, and this must come ultimately from the gravitational store of the galactic nucleus. If the energy source is the potential of the rotating central gas mass postulated above, then the situation I have described can last only a few galactic rotation periods. But if non-axisymmetric instabilities can permit gravitational coupling between the stars in the galactic center and the gas, the model can be maintained for perhaps a galactic lifetime. Of course, it must ultimately lead to the collapse of the central region with a large increase of the central angular velocity. The shocked region too, with its plasma and magnetic fields, would also spin very rapidly, and this may provide an avenue of the much-discussed dramatic evolution of galactic nuclei with accompanying large luminosities. But this phase of the problem cannot yet be discussed adequately.

References

Moore, D. W. and Spiegel, E. A.: 1966, in *Proceedings of the Summer School on Interstellar Gas Dynamics* (ed. by D. E. Osterbrock), Madison.
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Discussion

Oort: Referring to your remarks concerning the determination of the gravitational forces in the central part of the galaxy we have of course realized from the beginning that in the region where the large radial motions of the gas occur the gravitational forces could not be derived from the motion of the gas. However, within the rapidly rotating disk of 800 pc radius the rotation may well correspond approximately to the gravitational force. Rougoor and I have indicated that the observed run of the rotational velocity in this disk corresponds roughly to what one would expect if the density distribution in the nuclear region of our Galaxy would be similar to that in the Andromeda nebula (as inferred from the distribution of the light). Just outside the disk the transverse velocity of the gas seems to drop to quite low values.

Observations by Van der Kruit (in press) suggest that gas is ejected from the galactic nucleus under a large angle with the galactic plane. It is conceivable that at the radius where this gas falls into the disk this gives rise to the streams with low angular momentum.

Schmidt-Kaler: The dip in the rotation curve of the gas is very well shown in the Andromeda Nebula at 10′ from the centre according to very recent unpublished work of Rubin and Ford. However, a dip at this point appears also in the rotation curve of M31 as derived by Babcock (*Lick Obs. Bull.* (1939), No. 498) from the stars, and these are probably pretty old. How does that fit into your theory?

Spiegel: The rotation curve of the stars can of course be used to determine the mass distribution, assuming that the velocity dispersion in the stars is small enough and that nonradial gravitational forces are not large. The relevance of my remarks depends on whether there are appreciable differences between the rotation curves of the gas and the stars. If such differences exist, then I would claim that they are probably due to dynamical pressures or magnetic forces and the theory discussed may be relevant. This would be especially true if a pronounced relative minimum appears in the rotation curve of the gas. As I do not have the data of Rubin and Ford, I am not able to give here the results of such a comparison.