THEORETICAL CONSIDERATIONS ON THE DYNAMICS OF NORMAL GALACTIC NUCLEI

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I want to discuss the origin of non-circular gas motions observed in the nuclei of normal spiral galaxies and the possibility that recurring violent activity in normal nuclei excites such motion. But first, let us review several basic aspects of the nearest normal galactic nucleus -- the nucleus of our own Galaxy.

1. THE NATURE OF THE GRAVITATIONAL FIELD

The rotation curve as observed in the 21-cm line of neutral hydrogen gives some indication of the form of the gravitational field in the central region of the Galaxy. Figure 1 is a smooth fit to the rotation curve in the inner few kiloparsecs (solid line) taken essentially from the data of Rougoor and Oort (1960) and Simonson and Mader (1973). This rotation curve, within 1 kpc of the centre, is completely accounted for by the mass distribution implied by the extended 2.2-μ emission (Becklin and Neugebauer 1968, Oort 1971). Moreover, there is little doubt that this centrally condensed mass distribution should be identified with the bulge or spheroidal component of the Galaxy, because the spatial distribution of the 2.2-μ intensity is practically identical to the distribution of visible starlight in the bulge of M31 (Sandage, Becklin, and Neugebauer 1969). The conclusion is that the bulge overwhelmingly dominates the gravitational field inside of 1 kpc.

Sanders (1979) has given a mass model for the inner region of the galaxy consisting of a spherical component (bulge-halo) and a highly flattened disk. The spherical component has a density distribution inside 1 kpc which is consistent with the 2.2-μ intensity distribution (Sanders and Lowinger 1972). The rotation curve due to the spherical component alone is shown by the dashed curve in Figure 1; the difference between the dashed and solid curves indicates the contribution of the disk to the rotational velocity. It is seen that in this model the disk is becoming dynamically significant at radii greater than 3 kpc.

Given this model for the gravitational field, we can plot a few quantities of interest. Figure 2 shows Ω (the angular velocity of circular

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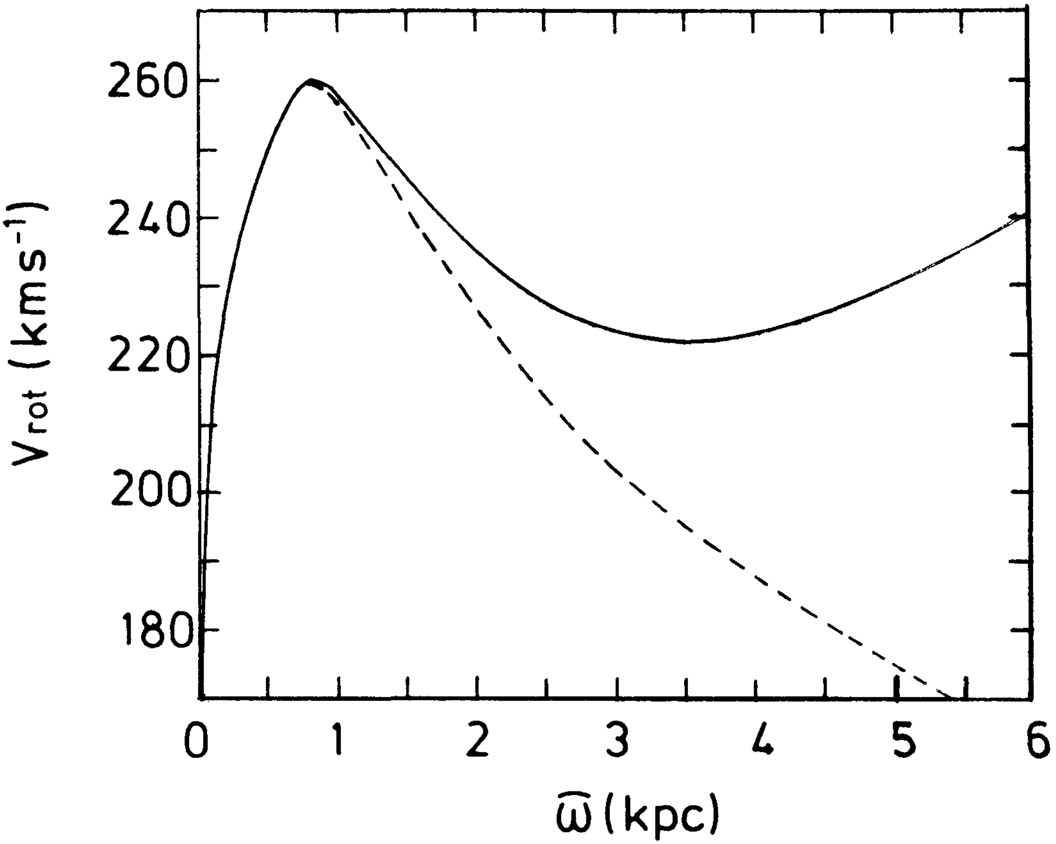

Figure 1. Rotation curve (solid line) in the inner region of the Galaxy and rotation curve (dashed line) of the bulge-halo component.

motion, $\Omega-\frac{\kappa}{2}$ (κ is the epicyclic frequency), $\Omega-\kappa$, and $\Omega-\nu$ (ν is the frequency of small oscillations in the z direction) as a function of distance from the center. The quantity, $\Omega-\frac{\kappa}{2}$, is the precession rate for a kinematic (zero mass) m = 2 distortion of the galaxy; i.e. a 2 - arm spiral or bar. Note that the pattern speed of a bar or spiral must be less than about 15 km s^{-1}-kpc^{-1} if it is not to wind up too quickly due to differential precession. The quantity $\Omega-\kappa$ is the precession rate for a kinematic m =1 distortion; ie. a one arm spiral or an off-set oval. This precession rate is negative which means that such a distortion would precess in a direction counter to galactic rotation. Also note that between 2 kpc and 6 kpc this precession rate is nearly constant, implying that a kinematic m = 1 distortion would be quite long-lived in this region. The quantity, $\Omega-\nu$, is the precession rate of a masseless annulus or ring which is slightly tilted with respect to the galactic plane. Obviously, tilted rings also precess in a sense counter to galactic rotation. This is the most uncertain frequency plotted here,

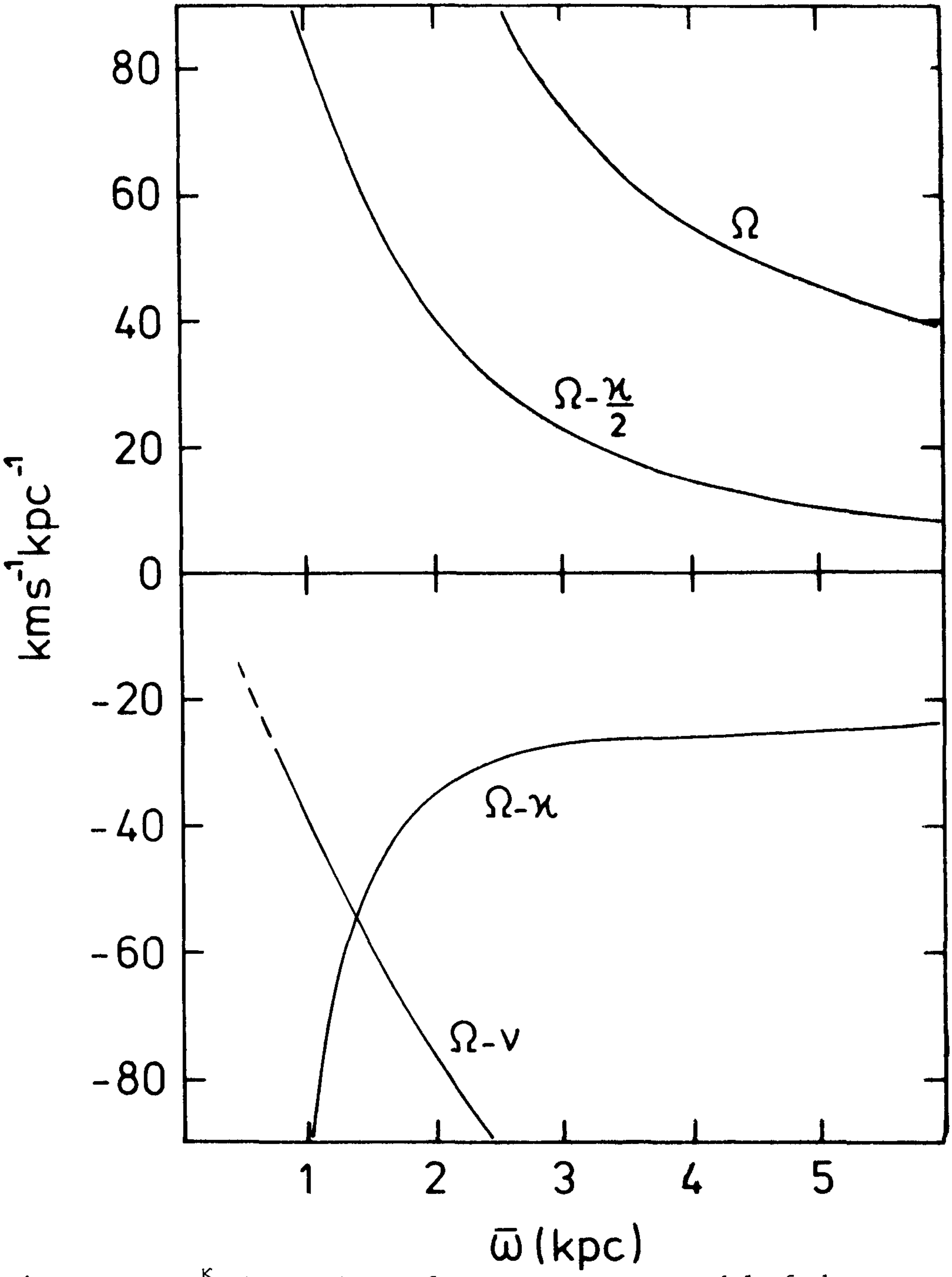

Figure 2. Ω, $\Omega-\frac{\kappa}{2}$, $\Omega-\kappa$, and $\Omega-\nu$ for a two-component model of the Galaxy giving the rotation curve shown in Figure 1.

because we really have no idea of the exact 3-dimensional shape of the mass distribution in the central part of Galaxy; however, for any mass model consisting of a dominant central spheroidal bulge and a more extended disk, $\Omega-\nu$ will have roughly this form. Note that $\Omega-\nu \approx \Omega-\kappa$ between 1 kpc and 2 kpc. I will return to this point in a few minutes.

2. NON-CIRCULAR GAS MOTIONS: $r > 1$ KPC

One of the most conspicuous features in the line profiles of neutral hydrogen and carbon monoxide is the 3 kpc arm. This "arm" discussed originally by Rougoor and Oort (1960) is located at a distance of 3 to 4 kpc from the center (judging from its longitude extent) and at zero longitude has a systematic motion away from the center of 53 km s^{-1}. The outward motion of the 3 kpc arm is almost certainly not caused by an explosion or violent ejection of matter from the center of the Galaxy. The most devastating argument against the explosion hypothesis was provided by Sanders and Prendergast (1974). This is ironic because in that paper we actually argued in favor of the explosion hypothesis. We demonstrated, by numerical hydrodynamical calculations, that in tremendously energetic event was required to excite non-circular gas motions in the plane at such large distances from the center -- something in excess of 10^{58} ergs. But even worse, it was also necessary to isotropically eject a mass in excess of 10^8 Mo. Otherwise the energy of the event escapes out the top and bottom of the Galaxy and has no effect on gas motions in the plane. This was a severe problem, even at that time, because observations of the 21 cm rotation curve put an upper limit of about 10^8 M☉ on a condensed mass at the center (Sanders and Wrixon 1973). But now we have a much more severe upper limit on the mass in the inner 1 pc, and that is 10^7 M☉ as determined from the Ne II line observations described by Dr. Lacy. This implies that we can't make the 3 kpc arm by an explosion; there just isn't enough mass in the center to isotropically eject. One might argue that 10^8 M☉ was in the core of the Galaxy, and it was ejected in the event that created the 3 kpc arm, and now its gone. But the problem is that such features are observed in the central regions of other normal galaxies, for example M31 (Roberts and Whithurst 1978). This means that we need such explosion going off every 10^8 years or so in order to maintain 3 kpc arms as more or less perminent features of normal galaxies, for example M31 (Shane, 1978). This means that of 10^8 M☉ in the cores of normal nuclei. If we assume a highly directional ejection, as in the model of van der Kruit (1971), the requirement for ejected mass can be reduced to 10^7 M☉, but even this is too much in light of the Ne II line observations.

So what does cause the 3 kpc arm? The 3 kpc arm is probably something like gas flow on elliptical stream lines due to the presence of a bar or oval distortion of the central region of the Galaxy. This has been suggested by de Vaucouleurs (1964) and Kerr (1968) and later modelled kinematically by Peters (1975) on the basis of a flow pattern suggested by Roberts (1971). I have recently carried out time dependent gas dynamical calculations of the flow in the central region of a galactic gravitational field which is distorted by a cos 2Φ perturbation (Sanders 1979). The axisymmetric form of the potential was the model described above: i.e., there were two components -- a bulge-halo and a disk. Only the disk was distorted by the cos 2Φ term; the bulge was assumed to be axisymmetric. The maximum azimuthal forcing occurred at 4 kpc and was 10% of the mean axisymmetric force at that radius. This is a weak m = 2 distortion in comparison with barred spirals, where the maximum tangential forcing may exceed 40% of the local axisymmetric force (Sanders and Tubbs 1980). The pattern speed of the m = 2 term was 13 km s^{-1} kpc^{-1} which gives an inner resonance at 4.4 kpc. This distortion produces flow on highly elliptical stream lines with non-circular velocities in excess of 70 km s^{-1} at radii between 3 kpc and 4 kpc. In the inner 1 kpc there is no non-circular flow because of the overwhealming dominence of the axisymmetric bulge. If the bar makes an angle of about 50° with the observer's line-of-sight, then the flow pattern reproduces the velocity-longitude locus of the 3 kpc arm -- with one significant exception: Since the gravitational field and, hence, the flow have 180° symmetry, there is an equally strong positive velocity counterpart to the 3 kpc arm. This is not observed. In fact, there are clearly large scale and systematic assymmetries in the neutral hydrogen kinematics in the inner 4 kpc of the Galaxy (see Oort 1977). One possible explanation for this asymmetry is the presence of an m = 1 distortion of the mass distribution in the inner Galaxy. As we have seen from Figure 2, there is a large region (3 kpc to 6 kpc) where a kinematic m = 1 distortion could persist for a long time. There is one other bit of observational evidence which might hint at the presence of an m = 1 distortion and that is the inner warp of the hydrogen distribution (Burton and Liszt 1978, Sinha 1979, Liszt and Burton 1980).

Dr. Liszt has shown maps of the integrated neutral hydrogen surface density within the velocity ranges 200 km s^{-1} $\leq |V| \leq$ 300 km s^{-1}. Since these are the highest neutral hydrogen velocities observed within the inner Galaxy, we can be reasonably sure that this gas lies near the sub-central radii. These pictures give the strong impression of a warp rather than a tilted disk. The hydrogen lies substantially within the galactic plane for $|\ell| < 4^\circ$, and the deviation from the plane only becomes significant in the region $4^\circ < |\ell| < 8^\circ$. But, as we see from Figure 2 this is precisely the region where $\Omega - \nu \simeq \Omega - \kappa$. That is to say, this is the region where oscillations perpendicular to the plane could resonate with an m = 1 distortion. This raises the question: could a off-set oval distortion of the galaxy drive a warp in the gas layer. This is essentially the same mechanism proposed by Binney (1978) for maintaining warps in the outer regions of galaxies. Sinha (1979) has suggested, in a general way, that the Binney mechanism might be responsible for the tilted distribution of neutral hydrogen in the inner Galaxy.

3. NON-CIRCULAR GAS MOTION: $r < 1$ KPC

Within 300 pc of the galactic center there are enormous molecular cloud complexes, such as Sgr A and Sgr B2 as well as the "expanding ring" first noticed by Scoville (1972) and Kaifu et al. (1972). This "ring" of molecular clouds is about 200 pc from the center and has a non-circular motion (in the sense of apparent expansion) on the order of 150 km s^{-1}. Its total mass is in excess of 10^7 M☉ implying a kinetic energy in expansion motion exceeding 10^{54} ergs (Bania 1977).

What is the likely cause of these high systematic non-circular velocities in the inner few hundred parsecs of the Galaxy? This problem is not peculiar to our own Galaxy since other spiral galaxies with nuclear CO emission also seem to require a large component of non-circular motion to account for the width of the CO line (Rickard et al. 1977).

I have argued that the non-circular motion of the molecular clouds does not result from flow on elliptical streamlines due to the presence of a bar (Sanders 1979). As we have seen, the gravitational field in the inner 1 kpc of the Galaxy is dominated overwhealmingly by the bulge. Now, in the oval distortion model for the 3 kpc arm described above I have supposed that the disk is ovally distorted and the bulge is axisymmetric. The basis for this conjecture is that flat stellar system supported primarily by rotation tend to be unstable to bar-forming modes; whereas, hot stellar system supported primarily by the random motion of stars are stable against bar formation (Ostriker and Peebles 1973). We have just heard from Professor Schwarzschild that tri-axial hot systems are dynamically possible, and that he has constructed at tri-axial model for the bulge of M31 where the axial ratio in the plane of the galaxy is 2:1. Of course, an equally valid interpretation of the isophote twist in M31 is an axisymmetric bulge and a barred or oval disk. This then is a fundamental question for disk galaxies: What is barred, the bulge or the disk? If we look at pure stellar barred system such as the SBO system NGC 2950 (Crane 1975) we find that the isophotes tend to get rounder closer to the center, implying that the central mass distribution is more nearly axisymmetric. However, there do seem to be several examples of barred spirals where the bulge itself is elongated perpendicular to the more extensive bar (Kormendy 1979). But if bulges, in general, tend to be more axisymmetric, then we have to look for another explanation for the non-circular gas motions of the molecular cloud region.

Allow me to speculate. If the expanding ring, described above, is an accurate description of the distribution of the molecular clouds 200 pc from the center, then an event of 10^{55} ergs to 10^{56} ergs is required every 10^7 years in order to keep the ring oscillating. How might such bursts of energy occur on this time scale? Dr. Lacy reported earlier that the Ne II line data is not inconsistent with the existence of a 5×10^6 M☉ black hole at the galactic center. Within 100 pc of the center, there are a number of massive molecular clouds (not belonging to the "expanding ring") with random velocities -- in excess of 50 km/s (such as Sgr A and Sgr B2). If we suppose that the motion of these clouds is completely random, and that there are on the order of 10 such clouds with diameters of 10 or 20 parsecs, then every 10^7 years one of these clouds will encounter the hole. Such an encounter between a black hole and a massive molecular cloud might be quite spectacular, and could easily produce the required 10^{56} ergs if the hole manages to capture 10^3 M☉ from the cloud (a small fraction of the mass of the cloud). Assuming a cloud size of 10 pc and a velocity of 50 km s^{-1}, the time in which the cloud is in contact with the hole is 10^5 years. Thus, every 10^7 years the nucleus of the Galaxy would experience an outburst with a duration of 10^5 years, an outburst producing a luminosity of perhaps 10^{44} ergs s^{-1}. For 1% - 2% of the time, our galactic nucleus would have a Seyfert luminosity. If this process is occuring in all normal spiral nuclei, then 1% - 2% of spiral galaxies should be Seyferts -- which is about right.

Of course this is mostly numerology, but we have heard today several interesting observational results which suggest that the occurence of activity in galactic nuclei is related to the availability of gas. I refer to the results reported by Drs. Liszt, Ekers and van der Hulst which suggest correlations of "activity" with

1) the presence of nuclear CO line emission;
2) the parent galaxy as one of an interacting pair;
3) classification of the parent galaxy as a SB or SAB.

Membership in a pair, or the presence of a bar might provide mechanisms for dumping low angular momentum gas into the nuclear region. At any rate, these results suggest that the engines for driving energetic activity may be available in all galactic nuclei, and that "normal" galactic nuclei are suffering --perhaps temporarily-- from a fuel crisis.

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