DYNAMICAL EFFECTS IN THE CENTRAL REGION OF THE GALAXY

Robert H. Sanders

Kapteyn Astronomical Laboratory
Groningen, The Netherlands

For the purpose of this Paper, I will define the central region of the galaxy as being the inner four kiloparsecs. I make this definition for three reasons:

1) Outside of four kiloparsecs, the rotation curve for the galaxy is well-defined by the Schmidt disk model; whereas, inside four kiloparsecs, the effects of a central spherical component on the rotation curve become conspicuous. This inner spheroid is a dynamical component of the galaxy which is distinct from the disk and may be distinct from the extended halo component as well.

2) There is a conspicuous hole in the total gas density distribution inside 4 kpc.

3) High peculiar or non-circular gas velocities are observed within the inner 4 kpc; velocities ranging from the 53 km s^{-1} of the so-called 3 kpc arm, to 165 km s^{-1} in the molecular clouds within 300 pc of the center.

I will now discuss these points in some greater detail.

I. The gravitational field:

The rotation curve as observed in the 21 cm line of HI is an indication of the form of the gravitational field. The 21 cm rotation curve in the central region of the galaxy was first described by Rougoor and Oort (1960) and is shown in Figure 1.
The existence of an inner component in the mass distribution, distinct from the disk or more extended distribution, is implied by the rapid rise to a peak at r = 800 pc. Independent confirmation of this central spheroid came in 1968 with the near-infrared observations of Becklin and Neugebauer. They discovered a source of extended emission at 2.2μ which they interpreted as being starlight and therefore an indication of the density distribution of stars in the galactic nuclear region. Making a few reasonable assumptions one can easily convert this observed 2.2μ intensity distribution into a stellar density distribution. This has

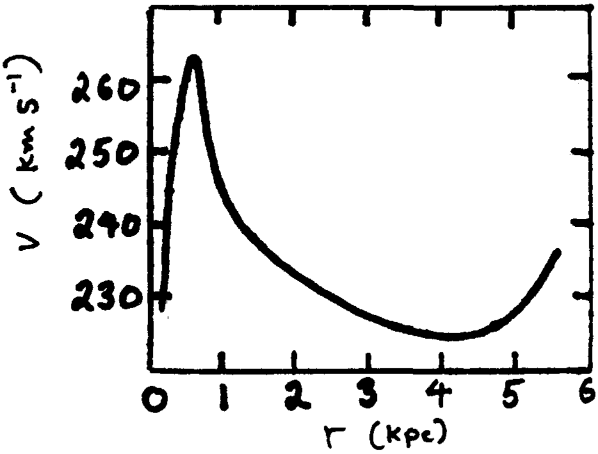

Figure 1: A sketch of the rotation curve in the inner 5 kpc of the galaxy (following Rougoor and Oort, 1960).

been done independently by Becklin and Neugebauer (1968), by Oort (1970), and by Sanders and Lowinger (1972). In particular, Sanders and Lowinger derive a stellar density distribution described by the formula

$$\rho(r) = \frac{7.6 \times 10^5}{r^{1.8}} \; M_\odot/pc^3 \qquad (1)$$

where r is the radial distance from the center in the galactic plane in units of parsecs. If we extrapolate this density distribution out to 800 pc (even though the actual observations correspond to radii less than 40 pc!) we may derive a rotation curve for the inner 1000 pc of the galaxy -- a rotation curve which is practically identical to the original Rougoor-Oort curve.

Now I would like to mention two general dynamical consequences of this observed central spheroid:

1) The density distribution in the spheroid is quite similar to that of an isothermal sphere. But in order to match the observed rotation curve beyond 1000 pc (specifically the decrease in rotational velocity) the isothermal sphere must be truncated at 800 to 1000 pc. Otherwise the rotation curve is flat from 1000 pc on out to the edge of the galaxy. This suggests that if the galaxy does have a massive spherical halo, then the central spheroid is dynamically distinct from it.

2) It has been suggested that high non-circular velocities in the

central region of the galaxy may be due to a bar- or oval-distortion, and, indeed, the spiral structure itself might be driven by such a non-axisymmetric distortion (Lin, 1970). If this is true then it is most certainly not the central spheroid but rather the disk component which is bar-like. The central spheroid is probably a hot, axisymmetric component. If this central component were a bar and truncated at 700 pc, its effect would be negligible at radii of 3 - 4 kpc where high non-circular gas motions are observed.

II. The overall gas distribution.

We have seen several times in this colloquium that the total gas density distribution, as indicated by the CO observations of Gordon and Burton (1976) increases proceeding inward from 10 kpc to about 4 kpc and then decreases rather dramatically; that is, there is a hole in the total gas density distribution inside 4 kpc. Dr. Peimbert has warned that we should perhaps not take this gas density distribution as derived from CO observations too literally due to abundance gradients; nonetheless, the total gas density as indicated by several tracers does seem to decrease inside 4 kpc by as much as a factor of four. The overall gas density distribution is indicated schematically in Figure 2.

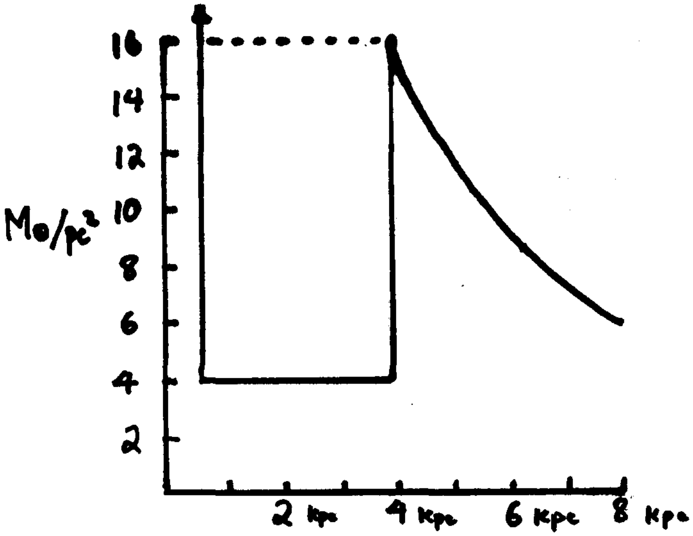

Figure 2: A schematic sketch of the distribution of total gas surface density. Dashed line shows the distribution if the 7×10^8 $M_\odot$ of gas in the inner 600 pc were distributed evenly over the inner 4 kpc.

One might ask how much gas would be required to fill in the hole inside 4 kpc. Just to fill it to the "brim" (with a surface density of 16 $M_\odot/pc^2$ as indicated by the dashed line in Figure 2) would require 7×10^8 $M_\odot$. Now, in fact, there is quite a bit of gas in the central regions, but it's all in the form of massive molecular clouds within the inner 600 pc of the galaxy. From the recent CO survey of the central regions by Bania (1977) we find a mean gaseous surface density in the inner 600 pc in excess of 500 $M_\odot/pc^2$ or, in other words, 7×10^8 $M_\odot$ of gas. If this gas were distributed evenly throughout the inner 4 kpc, it would (in some sense) fill up the hole. This suggests that inside 4 kpc, the gas has experienced some efficient loss of angular momentum, either due to viscous effects (as discussed by Dr. Ostriker yesterday) or perhaps due to breaking by a rotating oval distortion.

III. The peculiar gas velocities.

In the extensive review paper by Oort (1977), one may find a very complete description of the non-circular gas motions in the galactic center region. In discussing the general nature of these peculiar gas velocities, I would like to divide the galactic center region into three sub-regions. Such a sub-division is necessary because I will propose that the likely mechanism for excitation of high non-circular velocities is different in each of the three sub-regions. These sub-regions are indicated in Figure 3.

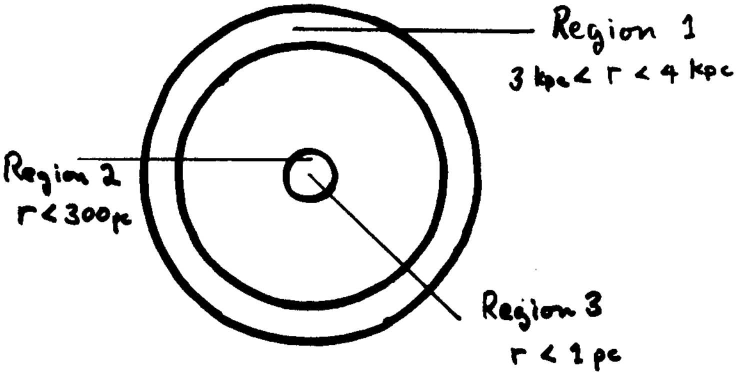

Figure 3: The galactic center region divided into three sub-regions where the nature of the non-circular gas motions may differ.

Region 1 is between 3 - 4 kpc; region 2 is between 100 pc to 300 pc from the center; and region 3 is the inner one parsec core of the galaxy. I will now discuss the character of the non-circular gas motions in each of these three regions.

Region 1: This is the region of the 3 kpc arm. This is a feature seen in 21 cm and molecular line observations. Its extent in galactic longitude indicates that it is at a distance of 3 - 4 kpc from the galactic center (Rougoor, 1964). It has an apparent expansion velocity (ie. radial motion directed away from the center) of 53 km/s, a total gaseous mass of 10^7 - 10^8 $M_\odot$ and a kinetic energy in expansion motion on the order of 10^{54} ergs. The question is - what is the cause of the radial or non-circular velocity component of this feature? First I will say what is probably not the cause.

It is not likely that the high non-circular velocity of the 3 kpc arm results from the perturbing effect of the classical Lin-Shu density waves at an inner Lindblad resonance (Lin and Shu, 1964). Huntley (1976), in time-dependent hydrodynamical calculations, has recently investigated the gas response to Lin-Shu waves in the vicinity of the inner Lindblad resonance. The form (ie. amplitude and wavelength) of the spiral waves in the region of the resonance was taken from the recent work of Mark (1974). Huntley finds no non-circular motions in excess of 25 km/s. This is esstentially due to the fact that the spiral waves are wrapping into a ring at the resonance; ie. the perturbing field is in fact becoming quite axisymmetric at the location of the resonance.

It is also not likely that the 3 kpc arm was caused by expulsions or super-explosions in the galactic center, as suggested in the work of van der Kruit (1971) or Sanders and Prendergast (1974). I won't give detailed arguments against this picture, but, suffice it to say, there seems to be no independent evidence for it.

The most likely explanation of the 3 kpc arm phenomenon is probably non-circular gas flow resulting from a bar-like or oval distortion of the central region of the galaxy. This was a suggestion first made by Kerr (1964). The difficulty of ascessing this proposal is that there exists no realistic stellar dynamical model of an ovally distorted disk or prolate configuration. Overlooking this fundamental difficulty I have recently done some time-dependent numerical gas dynamical calculations of gas flow in the central region of a galactic gravitational field which ovally distorted in a somewhat arbitrary way. The axisymmetric form of the potential was taken to mock up the central region of the galaxy; ie, there were two components: a central spheroid with $\rho \propto r^{-1.8}$ and truncated at 1 kpc, and a disk component with a Toomre (n = 1) potential (Toomre, 1963). The disk component was given a slight oval distortion described by a cos 2θ variation in the potential. Only the disk was distorted, not the central spheroid. The angular velocity of the distortion was chosen such that the inner resonance was between 3 and 4 kpc. The strength of the distortion was on the order of 10% of the axisymmetric disk component force. Gas motions were numerically followed until a quasi-steady state was reached in the rotating frame of the distortion. This steady state density distribution is shown in Figure 4.

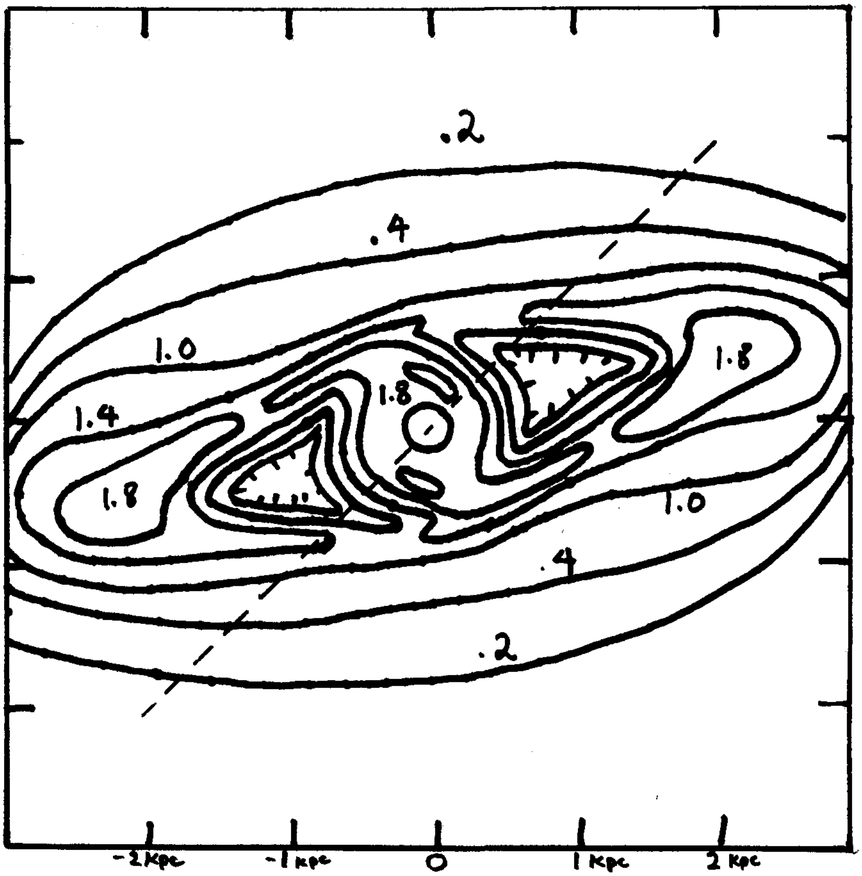

Figure 4: Steady state gas density distribution in the inner region of the galaxy assuming a 10% oval distortion of the disk gravitational field. Angular velocity of the perturbation is 16.7 km/s-kpc giving an inner resonance at 3 kpc. Density contours are in particles cm^{-3}.

This figure is a contour map of volume density in particles per cm^3 covering the inner 3 kpc. The dashed line indicates the major axis of the distortion in the gravitational field. Direction of the gas flow is clock-wise. The gas distribution is barlike except in the region of the inner spheroid where it becomes more axisymmetric. A contour map of the radial, or non-circular, component of velocity is shown in Figure 5. In the inner 1000 pc (the region of the central spheroid) it is seen that the motion is predominately circular. Between two and three kpc we see the "quadrapolar" pattern of inflow and outflow which is characteristic of gas on highly elliptical streamlines. Along a single line of sight to the center - one may easily observe outflow in excess of 50 km s^{-1}. These calculations show that a rather weak oval distortion can produce non-circular velocities of the observed magnitude. Whether or not the velocities have the observed character is a question that must be answered by detailed modelling. It is interesting to note that Rubin and Ford (1971) have shown that non-circular gas motions in the central region of M31 may have this characteristic quadrapolar form.

Region 2: This is the region of the very massive molecular clouds which have non-circular velocities in excess of 100 km s^{-1}. In Figure 6 we see a schematic sketch of the velocity-longitude contour map of 2.6 mm CO emission taken from the survey of Bania (1977). The different shading indicates the possibly distinct features of the emission. The solid shading is the most intense CO emission arising from clouds which have velocities that are generally permitted in the sense of galactic rotation. Here we see the massive Sgr A and Sgr B2 complexes as well as the nuclear disk of Rougoor and Oort. The cross-hatched shading indicates emission from the so-called expanding ring of molecular clouds first noticed by Scoville (1972) and by Kaifu et al.(1972). In this feature (if it is a continuous feature) there are non circular motions which are clearly in excess of 100 km s^{-1}. A kinematic model consisting of an expanding rotating ring may be fitted to this feature; this ring has an expansion velocity of about 150 km s^{-1}, a rotational velocity of 75 km s^{-1}, and a radius of 250 pc - 300 pc. Its mass must be on the order of 10^7 $M_\odot$ (Bania, 1977) and therefore the energy in expansion motion is on the order of 10^{54} ergs. Suggested explanations for this feature again range from resonance rings to super-explosions. For reasons discussed before, the field is very axisymmetric in the central few hundred parsecs of the galaxy; so it's a bit hard to understand the persistence of a resonance ring in the gas in this region. The super explosion hypothesis suffers from the same difficulty mentioned before with respect to the 3 kpc arm. Therefore, I would like to propose another possible mechanism.

The supernova rate in the galaxy is probably about $S = 2 \times 10^{-13}$ $year^{-1}$ $M_\odot^{-1}$. Assuming no variation of this rate with position in the galaxy, there will be a much higher density of supernovae in the galactic center region simply because of the much higher stellar

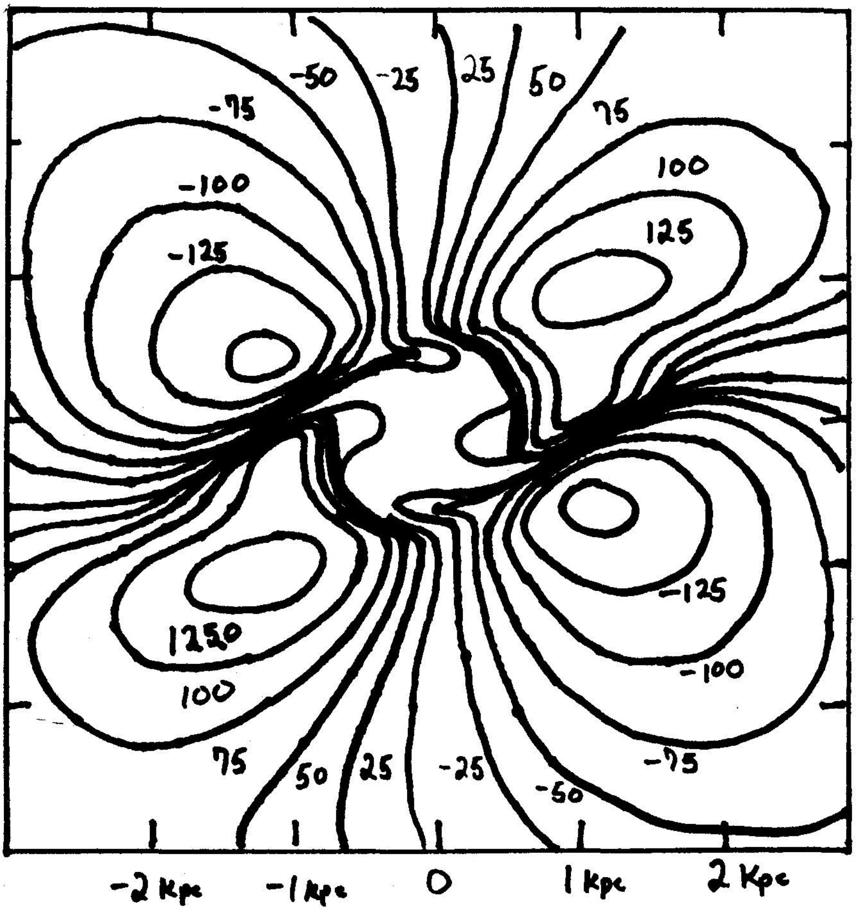

Figure 5: Contour map of the non-circular component of gas velocity for the model shown in Figure 4. Contour units are km s^{-1}.

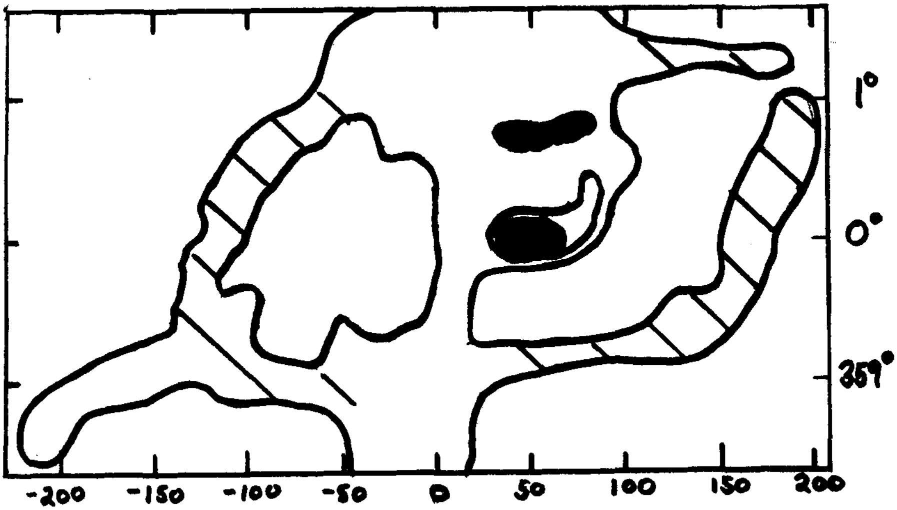

Figure 6. A schematic velocity-longitude contour map of 2.6 mm CO line.

density in this region. In the inner 300 pc (from the mass model given previously) there may be a total energy input from supernovae of

$$E_{SN} = 2 \times 10^{40} \text{ ergs/s}$$

assuming 10^{51} ergs per supernova.
Now let's compare this to the rate of energy dissipation, E_D, by the expanding ring. From simple ram pressure arguments

$$E_D = 2 \pi r \rho v^3 h$$

where ρ is the density of the ambient medium (1 cm^{-3}), v is the expansion velocity of the ring (150 km s^{-1}), r is the radius of the ring (300 pc) and h is the scale height (50 pc).
We then find that

$$E_D = 2 \times 10^{39} \text{ ergs s}^{-1}$$

or in other words, with a 10% efficiency for converting supernova energy into gas motions, we can make up for the energy being dissipated by the expanding ring.

Viewed simply the picture is this: In the vicinity of the sun, the random cloud velocities are on the order of 10 km s^{-1} and the rate of energy production per unit volume by supernovae may be 3×10^{-25} ergs/ $cm^3 s$ (Spitzer, 1968). In inner 300 pc this rate may be three orders of magnitude larger just because of the higher stellar density. Therefore, perhaps we shouldn't be too surprised if peculiar cloud velocities are also higher in this region.

The extended non-thermal radio emission of the source SgrA might, in fact, be the accumulated emission of the more recent supernova remnants. The total extent of the non-thermal emission is about 2° on either side of the center or roughly coincidental with the latitude extent of the expanding molecular clouds. There are several descrete non-thermal sources in this region as well (Oort 1977).

Region 3: Now I just want to briefly mention the inner one parsec core of the galaxy. In this region there are about $5 \times 10^6 M_\odot$ in stars (again from Becklin and Neugebauer, 1967). There is also $100 M_\odot - 200 M_\odot$ of ionized gas. The existence of this ionized gas is implied by the radio continuum observations of Balick and Sanders (1974) and Ekers et al. (1975); by radio recombination line observations by Pauls et al. (1974), and, more recently, by the 12.8μ Ne^{II} observations of Wollman et al. (1976). In particular the Ne^{II} line observations reveal peculiar velocities of 200 - 300 km s^{-1} (as reported in the previously mentioned review article by Oort, 1977), but due to the relatively low mass of gas the kinetic energy of non-circular gas motions in this region does not much exceed 10^{50} ergs.

These non-circular gas velocities may be related to what may turn out to be one of the most exciting objects in the galaxy. In the middle of this one parsec core, there sits a 2.2μ source (number 16 in the notation of Becklin and Neugebauer, 1975) with an extent of 2" - 3" (~.2 pc). The luminosity of this near infrared source is about $10^4 L_\odot$ and the spectral energy distribution in the near infrared is like that of the normal stars in the galactic center. From all appearances, this source might well be a cusp in the stellar density distribution at the very center of the galaxy. In the middle of this near-infrared source there sits an extremely compact radio source which was recently discovered by VLBI techniques (Kellerman et al. 1977). This central radio source has linear dimensions of less than 10 A.U. and a flat spectrum of continuous emission in the radio (Balick and Brown, 1974). If there is a candidate for a black hole at the center of our own galaxy, this is it; although the mass of this object cannot much exceed $10^6 M_\odot$ from the Ne^{II} observations.

REFERENCES

Balick, B., Brown, R.L. 1974, *Ap. J.*, 194, 265

Balick, B., Sanders, R.H. 1974, *Ap. J.*, 192, 325

Bania, T.M. 1977, *Ap. J.*, 216, 381

Becklin, E.E., Neugebauer, G. 1968, *Ap. J.*, 151, 145

Becklin, E.E., Neugebauer, G. 1975, *Ap. J.*, 200, L71

Ekers, R.D., Goss, W.M., Schwarz, U.J., Downs, D., Rogstad, D.H. 1975, *Astron. Astrophys.*, 43, 159

Gordon, M.A., Burton, W.B. 1976, *Ap. J.*, 208, 346

Huntley, J.M. 1976, unpublished calculations

Kaifu, J., Kato, T., Iguchi, T. 1972, *Nature Phys. Sc.*, 238, 105

Kellerman, K.I., Schaffer, D.B., Clark, B.G., Geldzahler, B.J. 1977, *Ap. J.*, 214, L61

Kerr, F.J. 1968, in *Radio Astronomy and the Galactic System*, IAU Symp. 31, Ed. H. van Woerden

Kruit, P.C. van der 1971, *Astron. & Astrophys.*, 13, 405

Lin, C.C. 1970, in IAU Symp. 38: *The Spiral Structure of our Galaxy*, eds. Becker and Contopolous

Lin, C.C., Shu, F.H. 1964, *Ap. J.*, 140, 646

Mark, J.W-K. 1974, *Ap. J.*, 193, 539

Oort, J.H. 1971, *Nuclei of Galaxies*, ed. D.J.K. O'Connell (Amsterdam: North Holland)

Oort, J.H. 1977, *Ann. Rev. Astr. and Ap.* 15 (in press)

Pauls, T., Mezger, P.G., Churchwell, E. 1974, *Astron. & Astrophys*, 34,327

Rougoor, G.W., Oort, J.H. 1960, *Proc. Natl. Acad. Sci. USA*, 46, 1

Rougoor, G.W. 1964, *Bull. Astr. Inst. Netherlands*, 17, 381

Rubin, V.C., Ford, W.K., Jr. 1971, *Ap. J.*, 170, 25

Sanders, R.H., Lowinger, T. 1972, *Astron. J.*, 77, 292

Sanders, R.H., Prendergast, K.H. 1974, *Ap. J.*, 188, 439

Scoville, N.Z. 1972, *Ap. J.*, 175, L127

Spitzer, L. 1968, *Diffuse Matter in Space* (New York: Interscience)

Toomre, A. 1963, *Ap. J.*, 138, 385

Wollman, E.R., Gaballe, T.R., Lacy, J.H., Towns, C.H., Rank, D.M. 1976, *Ap. J.*, 205, 15