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HOW ARE QUASARS FUELED? SIMULATING INTERSTELLAR GAS IN TIDALLY DISTURBED GALAXIES

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ABSTRACT

Galaxies with optical and radio emission in their nuclei such as Seyfert galaxies and quasars are more likely to have nearby companions than normal galaxies. It is usually suggested that inflow of gas to a black hole in the central region is required to fuel the nucleus of an active galaxy. Processes near the black hole are not part of this study. Instead, we will extend our previous investigations on whether gravitational tides from companions trigger global instabilities in spiral galaxy disks and thus rapid flows of gas into the nucleus to fuel activity. We will use an n-body computer program to simulate the disk of the spiral galaxy within a much more stable, high-velocity dispersion spherical halo. Under sufficient perturbation, the disk undergoes violent distortions due to the disturber and its self-gravitation. We have already simulated the tidal action of companions and shown that the tidal strengths at which the instabilities appear match those of the observed companions of Seyferts and quasars. With the additional modifications we have planned, the gas flow into the nuclear regions after the tidal interaction will be more realistically simulated to compare with observations (e.g. colors, velocity fields) of active galaxies. Work during this summer has involved learning the EADS system on the new IBM/Cray computer at Marshall, getting the computer programs used above working on the Cray, and doing library research on characteristics of the gas in disks of galaxies. Finally, I completed work on two articles not related to the above project.

ACKNOWLEDGEMENTS

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INTRODUCTION

It has become increasingly apparent that excess optical and radio emission in nuclei of galaxies and quasars is related to the presence of companions (Sulentic 1976, Hummel 1982, Stauffer 1982). Seyfert galaxies with strong activity appear to be more likely to have companions than normal galaxies (Adams 1977, Vorontsov-Velyaminov 1977, Simkin et al. 1980, Balick and Heckman 1982, Kennicutt and Keel 1984, Dahari 1984, Cutri and McAlary 1985, Keel et al. 1985). Furthermore, the same correlation is seen for quasars (Stockton 1982, Hutchings and Campbell 1983).

It is usually suggested that an inflow of gas to the central region of a galaxy is required in order to fuel the nucleus of an active galaxy or quasar (Simkin et al. 1980). The inflowing gas will form an accretion disk (Bailey 1982, Bailey and MacDonald 1981). Usually the disk is thought to build up from various possible inflows and to become unstable due to some intrinsic mechanism either local or global (Bailey 1982, Tanaka et al. 1984).

Another earlier suggestion for fueling of central engines of tidally interacting galaxies has been disk gas transfer from a closely passing spiral companion to its primary (e.g. Toomre and Toomre 1972, Keel et al. 1985). While this mechanism may occur and is worthy of future study, we feel that the feeding from the disk of a spiral itself into its nucleus is probably more important. Evidence for this conclusion is Daharis' (1985) observation that in interacting pairs of galaxies, Seyfert nuclei are found exclusively in the spiral members, not in elliptical members. If gas flow from companions is responsible, then ellipticals would be just as likely to show Seyfert activity in pairs as spiral members would.

OBJECTIVES

1) Become familiar with the EADS system on the new IBM/Cray computers at Marshall Space Flight Center.

2) Make all changes necessary to get the Miller Polar N-body program (previously used to study tidal triggering of Seyfert galaxies) working on the Cray.

3) Review astronomical research on the nature and dynamics of the interstellar gas in the disks of spiral galaxies.

4) In the light of current knowledge about disk gas, plan and implement changes in the Miller Polar N-body program to more realistically simulate the fueling of Seyfert/Quasar activity in nuclei of tidally disturbed galaxies.

PREVIOUS WORK

Because of the observed correlation between such activity and the presence of companions, we have investigated whether gravitational tides may provide an external triggering mechanism (Byrd et al. 1986c). These tides should precipitate global gravitational instabilities in the disks of affected spiral galaxies and thus rapid flows of disk matter into the nucleus. Prior to the encounter the Seyfert galaxy would be much quieter since its disk would be stable and the nuclear black hole would not be fueled rapidly.

It has been suggested that bar distortions in the nuclear bulge could act to feed the nucleus with disk material (see Balick and Heckman 1982 review). However, the observational correlation of strong Seyfert activity with the presence of companions indicates that the tidal mechanism is one way that Seyferts may be made. The tidal mechanism is an "avalanche" process in that, once it is triggered, global instability by self-gravitation of the disk can create high levels of inflow. In contrast, an intrinsic bar mechanism could be a continuous, nonaccumulative and thus lower level process. The two mechanisms do not exclude one another and could be important for different levels of Seyfert activity. Indeed, we observe a bar to form in our model galaxy under strong perturbations so there may be a connection between the two mechanisms. Thompson (1981) has observationally verified the connection between spiral galaxies having a bar and tidal action finding a larger fraction of galaxies to be barred in the core of the Coma Cluster than outside.

In our earlier work, we required that instabilities be provoked in less than two revolutions of the disk edge since we are considering the more active Seyferts and quasars. Two revolutions of the disk is also about the length of time for strong tidal perturbation in an encounter of two galaxies. Our emphasis was on whether the tidal field is sufficient to induce global disk instabilities. We required that gas flows through the central regions match those commonly cited as being required for Seyfert activity (~0.5 solar masses/yr, Balick and Heckman 1982).

Our principal tool was a two-dimensional polar coordinate FFT n-body program by Miller (1976, 1978). The coordinate grid of this program is well suited for study of disk galaxies providing high spatial resolution where it is most needed near the center. We used about 60,000 particles to simulate the disk of the spiral galaxy. Each part of the disk acts gravitationally on all other parts of the disk.

The spiral galaxy disk was composed of stars and gas. The program has been used to study the onset of global instability and subsequent changes in a disk composed primarily of stars (Miller 1978). The unmodified program has also been used to study the onset of global instabilities in a gaseous disk (Cassen, Smith, Miller 1981). We have modified the program to simulate a finite Mestel disk (Mestel 1963, Lynden-Bell and Pineault 1978) rather than the infinite disk studied by Miller and co-workers. We also modified the program to simulate the tidal effect of a companion on the disk of a spiral galaxy. We also used this version to study the orbital decay of satellites of disk galaxies (Byrd, Saarinen, Valtonen 1985, 1986) and the creation of spiral arm spurs by large gas complexes in galaxy disks (Byrd, Smith, Miller 1984). These extensions of the program were also necessary for our simulation of tidal triggering.

Besides the strength of the tidal field, the other major parameters of our study were the ratio of the halo mass to the disk mass and the velocity dispersion in the galaxy's disk. We expect the halo to have a high velocity dispersion and therefore be much more stable than the "cooler" disk. Accordingly, we followed Miller (1978) and consider the halo to be inert. Increasing the halo to disk mass helps stabilize the disk, as does increasing the disk velocity dispersion (Toomre 1964). The spatial softening due to the program grid and a constant in the gravitational potential formula assumed have the same stabilizing effect as the velocity dispersion (Miller 1971, 1974, 1978). Using Miller (1978), the spatial softening of our model disk is equivalent to a velocity dispersion of about 1.5 times that sufficient to stabilize it against small asymmetric perturbations. This assumed dispersion is about that seen in stellar disks of spirals. We initially kept the disk velocity dispersion softening fixed at the observed value, but we tried various halo to disk mass ratios. Figure 1 shows examples of the disk evolution of two disturbed galaxies.

Our fundamental method for estimating gas flow into the nuclear regions was very crude. We simply counted how many of the 60,000 disk particles per time step were thrown into orbit crossing the 1 kpc nuclear region. This fraction x the assumed fraction of the disk in gas (0.10) x the assumed disk mass (1×10^{11} solar masses, 20 kpc) equalled the rate gas entered the nuclear regions. As mentioned earlier, the rate was required to be $\gtrsim .5$ solar masses/year. This gas, once thrown into such orbits, will collide with other such gas inelastically to flow into the "engine". We emphasize that small scale accretion processes near the central black hole were beyond the scope of our investigation.

Should the reader have any doubt about the ability of intrinsic instability to prevoke substantial inflows into the central regions of a spiral galaxy under the proper circumstances, we describe the following example result from our previous work. As described earlier, this program provides a crude view of flows of former disk gas through the central regions of a perturbed spiral galaxy. We assume here a ~20 kpc, 3×10^{11} solar mass disk with no spherical halo. This disk is perturbed just enough to induce global instability by a ~ fixed distant disturber. (The perturbation = mass perturber in terms of disk mass/ (distance of perturber relative to disk radius)^3 ~0.01). This perturbation equals that caused by, for example, an equal mass companion at 5 disk radii from the center. Results are shown in Fig. 2. The inflow starts about 200×10^6 yr after the perturbation starts. This delay is approximately the free fall dynamical time scale of the disk. The first inflow is a violent episode at 300 solar masses/year with the peaks of subsequent episodes declining roughly exponentially over several hundred million years to a fairly smooth inflow of a few solar masses/year. The total amount of gas thrown into nucleus-crossing orbits is about 5×10^9 solar mass in $\sim 600 \times 10^6$ yr $\approx$ 10 solar masses per year. The angular momentum removed from this disk material has been (of course) transferred to other disk material.

Note the "latency time" of $\sim 200 \times 10^6$ yr seen in our preliminary runs. The material has not fallen into the nuclear regions until after the companion has moved away from the perigalactic point of strong tidal action. Thus not all galaxies strongly perturbed by companions have to be active at the time we are observing them.

According to our simple previous calculations, tidal perturbations somewhat weaker than our example above result in much weaker inflows in our model. Also, if we add an inert halo several times the disk mass, stronger levels of perturbation about 25 times greater are required to produce the inflows thought necessary for Seyfert activity. At very high halo masses, self gravity should not be important. There the tidal field dominates in generating inflow.

Perturbation levels of 0.01 to 0.1 are required depending on the mass of the halo. Dahari finds that most spiral galaxies perturbed at these levels or greater are Seyferts.

In additional previous work (Byrd et al. 1986b), we found evidence that the tidal mechanism is probably the main cause of Seyfert activity. In an examination of Seyfert galaxies not in groups with redshift $z < .03$, Dahari (1984, 1985) found that about 1/3 of these Seyferts had observable companions with approximately the same z. There are various selection effects to cause companions to be missed: misidentification of small companions as stars at higher z and failure to find companions beyond Dahari's search radius around the Seyfert. Examining the low redshift portion ($z < 0.01$) of Dahari's sample, we estimate that at least 3/4 or possibly more of Dahari's Seyferts have companions. This high proportion thus implies that tidal interactions may be the predominant cause of Seyfert activity.

Our self-consistent n-body simulations of satellites orbiting disk galaxies (Byrd et al. 1985, 1986a) and the semi restricted simulations of Quinn and Goodman (1986) indicate the companions of disk galaxies should sink into ever smaller orbits and eventually merge with the other galaxy. Most of the apparently solitary Seyferts with $z < 0.01$ in Dahari's sample are of E or SO Hubble type. Merging of spirals with companions is thought to change spirals to these Hubble types (Tremaine 1981, Veeraraghavan and White 1985). So even truly solitary Seyferts may have had their activity induced by tides or merging. The existence of one "multiple" nucleus Seyfert in Dahari's sample further supports this picture.

CURRENT AND PLANNED WORK

During this summer I have learned to use the IBM-EADS and Cray computer systems at Marshall. I have now gotten the computer program used in the above work functioning on the Cray. I have also been doing library research and discussing with colleagues here how to better model the gas flows into the nuclear regions of the disturbed galaxies. During this coming winter and the following summer, these modifications will be incorporated into the present program. Finally, during this summer I completed two papers unrelated to the above project: "Explaining the Holmberg Asymmetry in Systems of Galaxies" and "Leading Arms in Spiral Galaxies" which will shortly be submitted for publication.

Since they will be important in future work, the results of my library research on how to model the gas for interacting galaxies will be discussed here. Our previous calculations simply counted how many of the 60,000 disk particles were thrown into orbits crossing the ~1 kpc nuclear region. Here we describe the results of our current library research on the nature of the disk gas in our galaxy to better model what happens to nucleus crossing gas clouds.

After carefully examining other approaches which assume the disk gas to be continuous (Hockney and Eastwood (1981) and Gingold and Monaghan (1982)), we feel that the cloud/particle model best describes the interstellar matter in our galaxy since the gas has been found to be inhomogeneous. This conclusion presumably applies to other similar spiral galaxies. Most of the galactic interstellar medium lies in denser regions ("clouds") which fill only a small fraction of the volume (Spitzer 1978, McKee and Ostriker 1977). While the global behavior of these clouds can under some circumstances be modelled like a gas continuum, representation of events on scales of a few hundred parsecs is better done by the cloud/particle model (Cowie 1981, Roberts and Hausman 1984).

How shall we model the swarm of clouds which make up the gas in the disks of spiral galaxies? We can surmise that the "gas clouds" counted in our previous work will suffer inelastic dollisions with other clouds as they cross the nuclear regions. These collisions will cause theorbit to shrink and the gas will eventually feed the giant black hole or other engine surmised to exist at the centers of active galaxies. The work planned at MSFC will test this important "collision/shrinkage" point.

Miller (1971) pioneered a simple "sticky particle" method of simulating gas in the disks of galaxies. However, for our goals a more complicated approach will be necessary. Levinson and Roberts (1980), Roberts and Hausman (1984), Hausman and Roberts (1984), and Noguchi and Ishibashi (1985) have described and used a cloud/particle model for the disk interstellar gas of spiral galaxies. This model successfully describes the shocks in the arms of a spiral galaxy and appears to be suitable for our program.

We plan to follow Roberts, et al. in including the cloud/particle model in our present two-dimensional program. Several thousand of our present particles will be designated as representative gas clouds. Our disk of gas and stars will be self-gravitating in contrast to all the previously mentioned applications of the Roberts et al. cloud/particle method. The model gas clouds collide inelastically with one another within a certain close approach distance determined by observations in our galaxy.

It has been found that most of the mass of the gaseous disk interior to the sun's orbital radius is in molecular hydrogen clouds ($\sim 5 \times 10^9$ solar masses. Beyond the sun's orbital radius the hydrogen is primarily atomic (in clouds). The molecular cloud surface density peaks at 6 kpc from the center with a minimum near the nucleus (see review by Mihalas and Binney 1981). The gaseous disk is very thin (~120 pc). Numerically, most of the clouds have cold cores ($\lesssim 2$ °K). These are scattered evenly over the disk in angle. A typical mass for these many thousands of clouds is $\lesssim 10^5$ solar masses. These clouds are probably rather old ($\gtrsim 10^8$ yr) because of their smooth disk distribution (Soloman and Sanders 1986) (see Fig. 3). These clouds are probably cold because bright, massive blue stars are not being formed in them (Elmegreen 1986). The velocity dispersion among the clouds is a few km/s, much smaller than the disk stellar velocity dispersion.

In contrast, another population of clouds, those with warm cores (~11 ^{0}K) are concentrated in the spiral arms. These clouds are outnumbered ~3/1 by the cold clouds. Formation of groups of O/B stars evidently warms these clouds. These clouds are mostly aggregated in complexes above 10^5 to as large as 2×10^6 solar masses (Soloman and Sanders 1986) (see Fig. 4). The formation of these comlexes is apparently the result of inelastic encounters among the clouds when they are crowded together in the stellar spiral arms of the disk (Kwan and Valdes 1983, Tomiska 1984). It may be that star formation and gravitational tides upon leaving the spiral arms breaks up these complexes. They are not found outside the arms and O/B star associations in them are 10 to 20 million years old, the time to cross an arm.

Our model then will be a similar to that of Roberts and co-workers mentioned previously. Besides the information mentioned above, we will need the observed mass distribution $n(M)dM = 10^{3.2} M^{-1.5} dM$ (m in solar masses, n in number/kpc^2). We will also need the size versus mass relation $M = 118 \text{ size}^{2.25}$ (size in pc)(Elmegreen 1986).

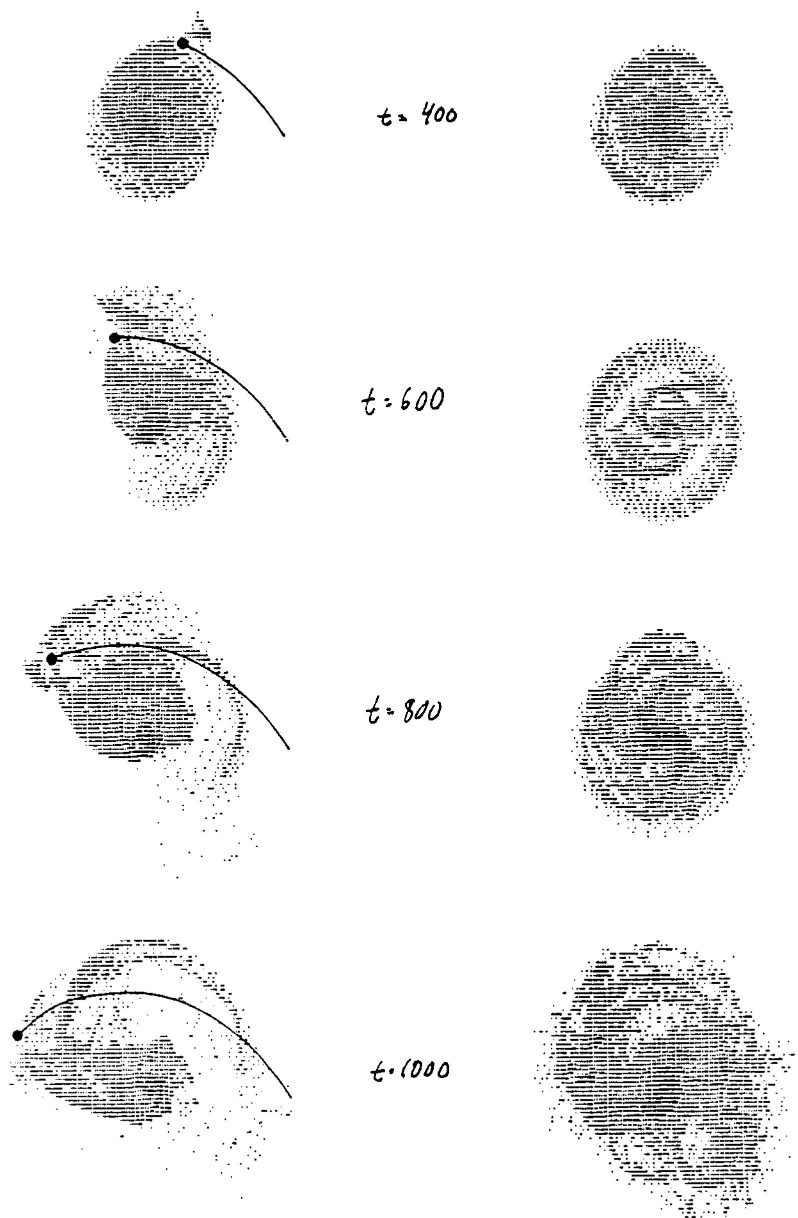
With this information, we can roughly estimate the cross section for inelastic collisions and other model parameters.

CONCLUSIONS

In contrast to all previous simulations, our model will have a self-gravitating disk of stars and gas clouds. We will be able to model "coagulation" of cloud complexes by inelastic collisions and their dispersal by star formation as others have done. However, we can also include the formation of the large complexes by gravitational attraction and their dispersal by gravitational tidal forces as they leave spiral arms. We should be able to model much more realistically the process of energy and angular momentum loss among clouds thrown into nucleus-crossing orbits in our Seyfert/guasar models. Besides this, our models may also shed light on the life cycle of the giant molecular cloud complexes in the disk of our galaxy. Now that the basic program is fully functional on the Cray here at Marshall and current literature on gas in our galaxy studied, we are now in a position to make our model much more realistic.

Figure 1. Examples of disk evolution of two disturbed galaxies. Vertical sequence on left is a close encounter with the companion in same sense as disk spin approaching to two disk radii. Companion is 0.4 of disk mass. There is an inert halo 0.5 of disk mass.

The right band vertical sequence is the effects of a slowly moving distant disturber 30 disk radii away, 316 times the disk mass. This disk has no halo. One time step is roughly one-half million years.



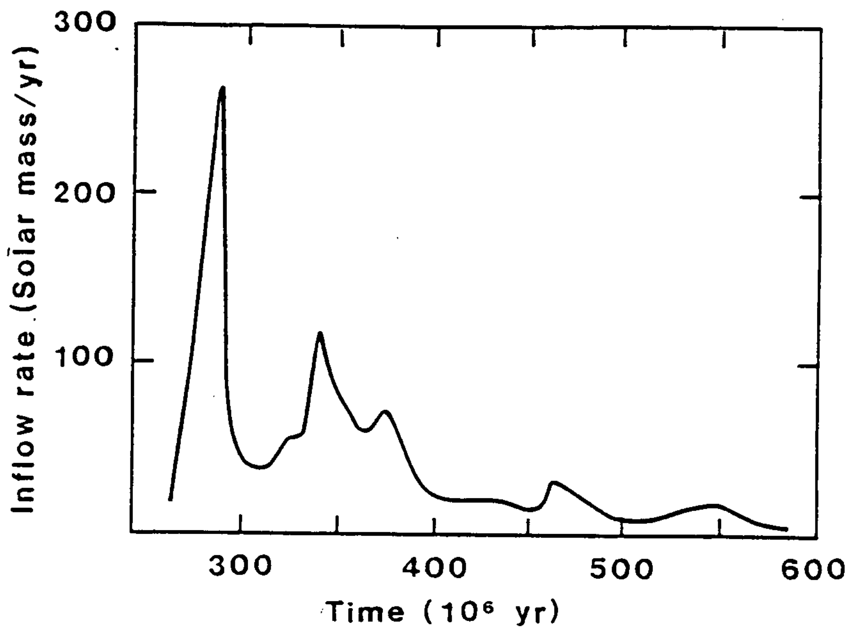


Figure 2. Estimated gas inflow rate for the right hand disturbed galaxy in Figure 1. Ten percent of disk mass is assumed to be gas. Disk particles are counted when they cross the nuclear regions. A particular, once counted, is tagged and not counted again. To get the gas flow, the disk mass is assumed to be 3×10^{11} solar masses.

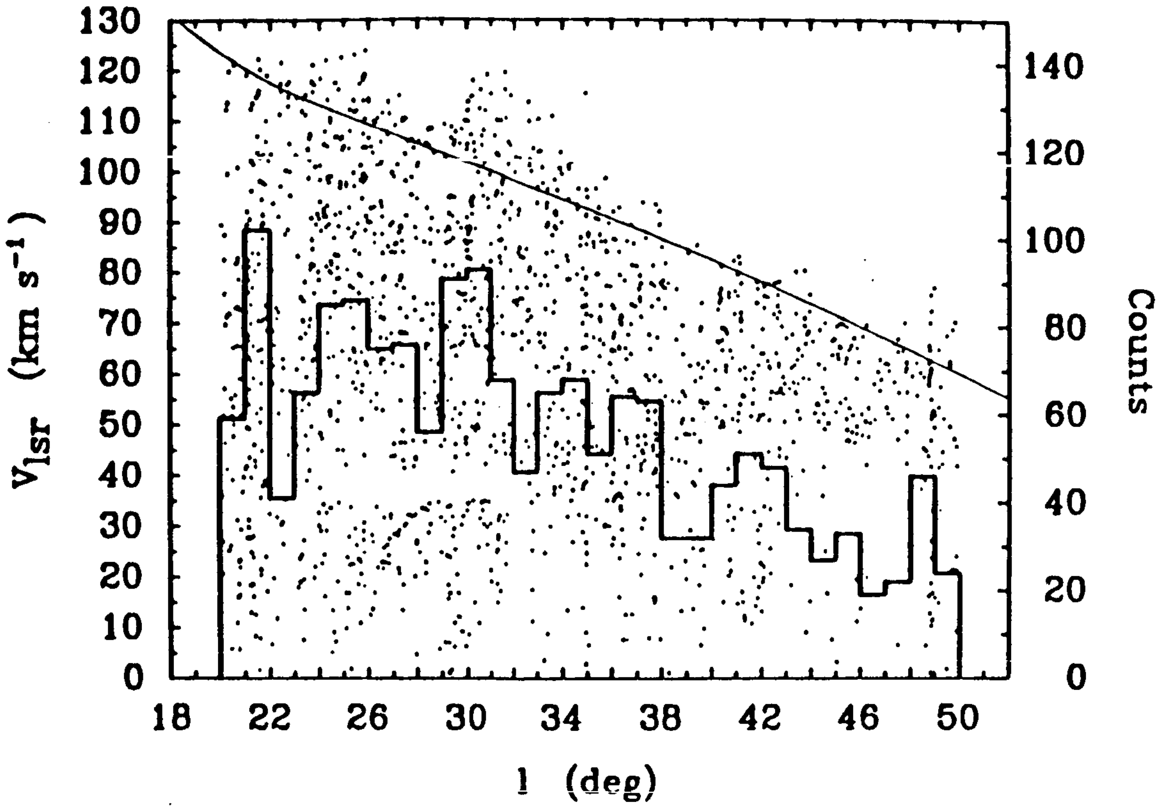


Figure 3a. Disk orbital velocities relative to the earth of the cold molecular cloud cores indicated by dots plotted according to their angle along the Milky Way from the galaxy center. Clouds within 0.4° north and 1° south of the Milky Way plane are shown. Contrast with Fig. 4a.

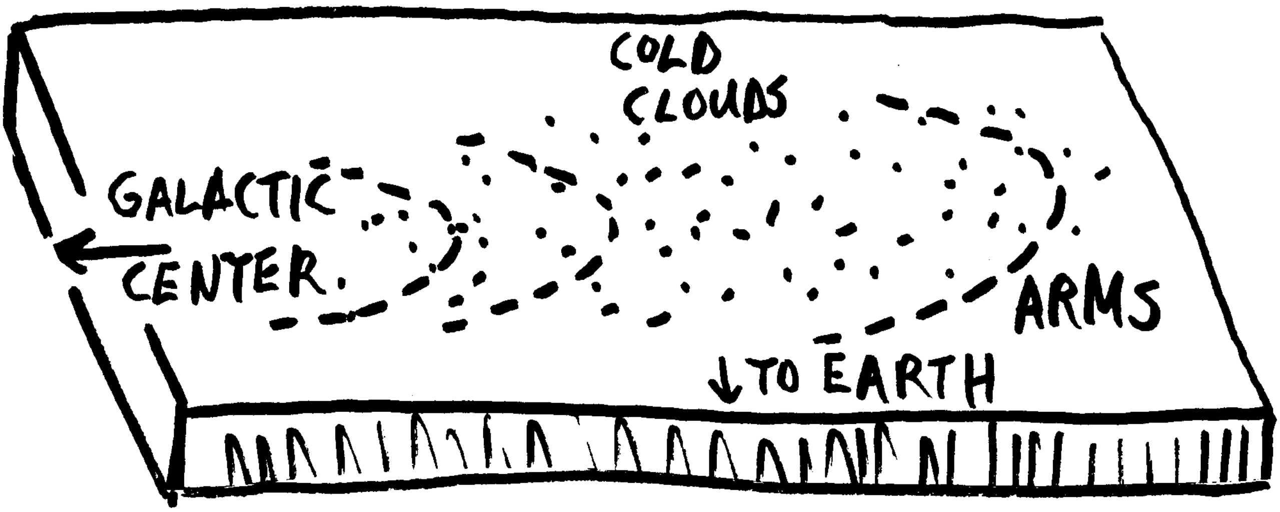


Figure 3b. Schematic drawing of the locations of the cold molecular cloud cores (dots) to the spiral arms on part of the disk of our Milky Way galaxy. Contrast with Fig. 4b.

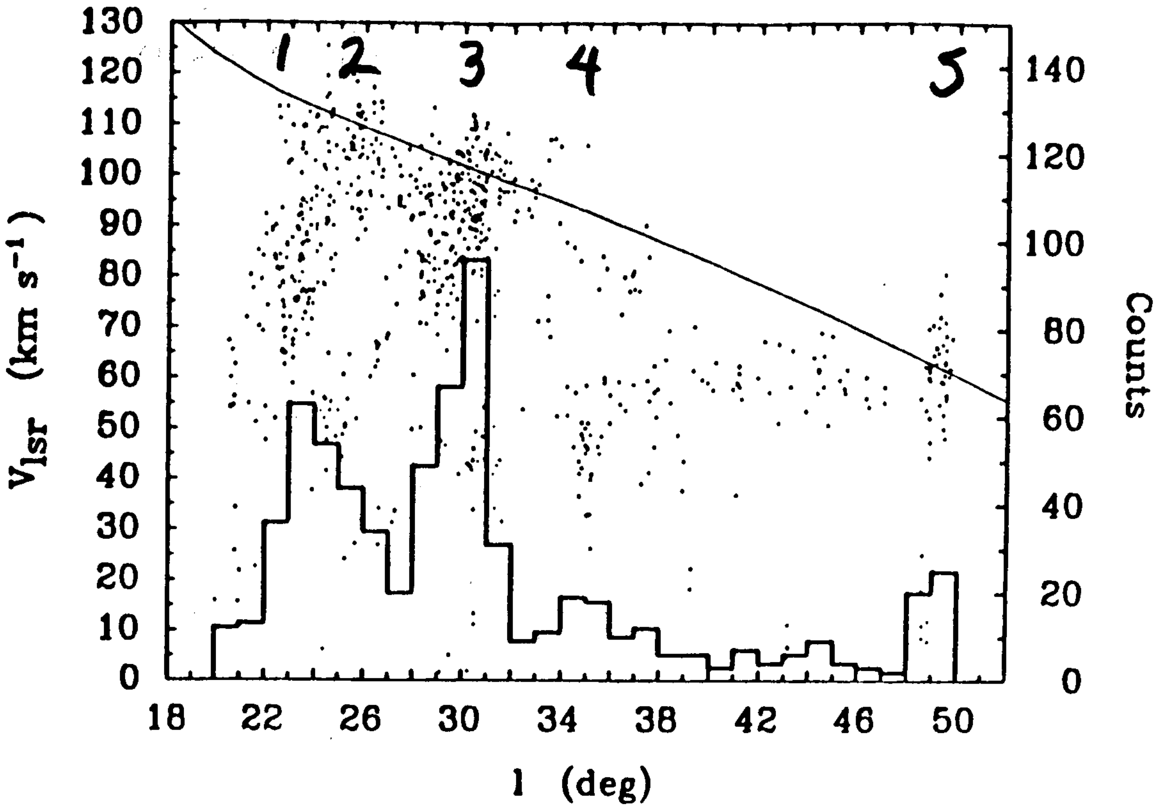


Figure 4a. A plot of warm molecular cloud core velocities and angular positions (compare to Fig. 3a). Note that the cores are in groups whose members are spread out vertically by their orbital velocities in the groups. Also note the peaks in the histogram corresponding to spiral arms seen tangentially at 24°, 30°, and 50°.

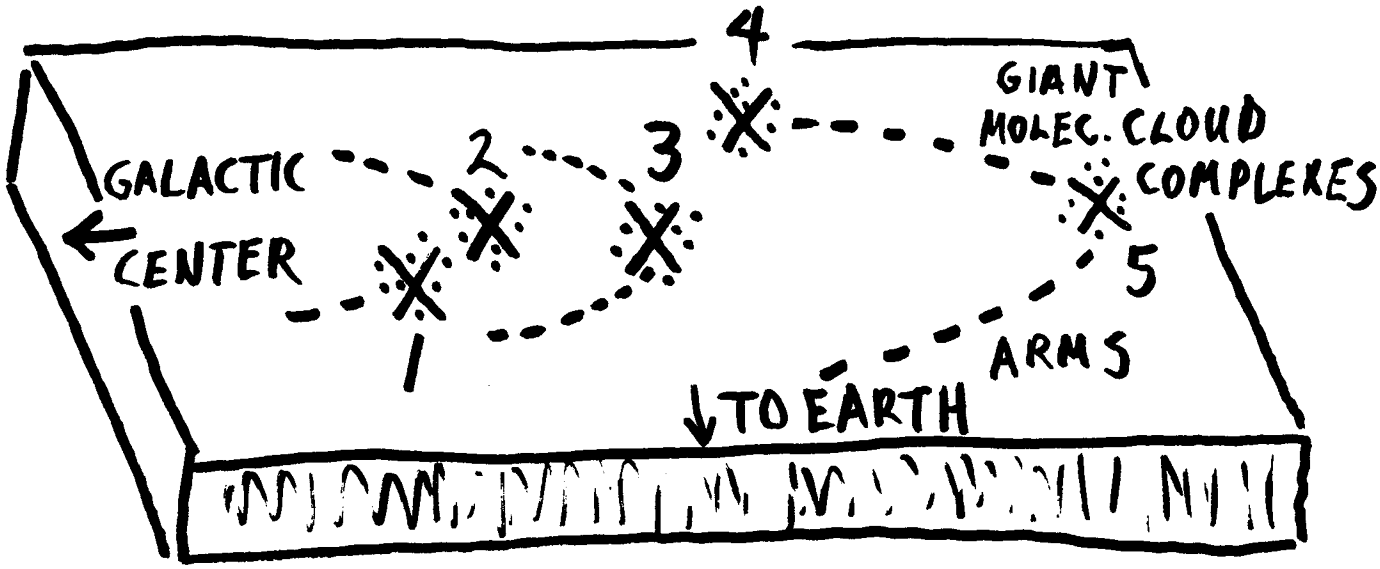


Figure 4b. Locations of the warm molecular cloud cores grouped in giant molecular cloud complexes along spiral arms in the disk of our galaxy (compare to Fig. 3b).

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