

Summary: Inflows and Outbursts in Galaxies

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1 INTRODUCTION

A wealth of information has been presented at this conference illustrating the basic theme that large-scale gas inflows can result in the release of large amounts of energy in galactic nuclei by starbursts and by non-thermal processes associated with black hole accretion. Particular attention has been paid to two situations in which such phenomena frequently occur: (1) bar-driven inflows in barred spiral galaxies can lead to gas accumulation and star formation in nuclear rings of ‘hot spots’, and (2) tidal interactions and mergers between galaxies can cause large amounts of gas to fall rapidly into their nuclei and produce luminous starburst and non-thermal activity. Although it is difficult to observe the gas inflows themselves directly, partly because they may be masked by more conspicuous outflows, inflows are commonly predicted by numerical simulations of barred and interacting galaxies, and the success with which these simulations match many of the observed properties of such systems leaves little doubt that inflows occur quite generally whenever a non-axisymmetric gravitational potential is present. Evidence that gas inflows from regions of galactic size are responsible for triggering the most energetic outbursts of activity in galactic nuclei is provided by the fact that in many of the most luminous systems, an amount of molecular gas comparable to the gas content of an entire large spiral galaxy is observed to be concentrated into a small nuclear region only a few hundred parsecs across.

Starbursts and non-thermal activity in galactic nuclei have two major consequences for galactic evolution: star formation and the growth of black holes can build up the central regions of galaxies, and the energy so released can heat and expel residual gas into an intergalactic medium. Thus an understanding of how gas condenses into galactic nuclei is an important part of understanding the evolution of galaxies and of the universe as a whole. Much remains to be learned about the many processes involved, especially on the small scales relevant to black hole accretion, but considerable progress has been made in recent years in understanding the mechanisms that operate on galactic scales, thanks to a fruitful combination of observational and theoretical studies, as has been evident at this meeting. As a result, a good understanding is beginning to emerge of how bars and tidal interactions can

cause gas to accumulate in nuclear regions less than a kiloparsec in radius, and the possibility that similar processes operate on even smaller scales and play a role in black hole accretion is currently a subject of active study.

In several respects, there is a close analogy between the condensation of gas in galactic nuclei to form central black holes and the condensation of gas in protostellar clouds to form stars. In both cases, gas that was initially widely distributed condenses under its self-gravity into a region many orders of magnitude smaller in size, and the energy released creates not only a high luminosity but also vigorous outflows that can dominate the observed properties of the system. There are also similar requirements in the two situations that the gas must lose nearly all of its angular momentum if it is to become highly condensed, and the mechanisms involved in the transport of angular momentum may even be similar. The mechanisms that act to redistribute angular momentum on galactic scales and drive gas inflows into galactic nuclei are summarized in the next section; most of the effects discussed also operate in other contexts, such as star forming clouds, and therefore are of more general interest.

2 GRAVITATIONAL MECHANISMS

Most presentations at this conference have dealt with phenomena that occur on scales larger than a hundred parsecs, where gravity is almost certainly the dominant force. The basic theoretical problem, in the galactic as in the stellar case, has usually been taken to be the need to understand how angular momentum is removed from the condensing gas. Angular momentum has played a key role in cosmogonical discussions because it has traditionally been assumed for simplicity that the initial configuration is spherical and has a central force field; angular momentum is then a conserved quantity, and gas that initially has any significant non-radial motion must overcome an ‘angular momentum barrier’ if it is to become highly condensed. In reality, of course, astronomical systems need not begin with spherical or even axial symmetry, and angular momentum is then not in general a conserved quantity and there need be no ‘angular momentum problem’. Nevertheless, since most observed galaxies do show approximate symmetries, it is still a useful approximation to discuss their structure in terms of departures from axial symmetry and their dynamics in terms of torques that can redistribute angular momentum. Several mechanisms for redistributing angular momentum can be distinguished that are associated with different types of non-axisymmetric disturbances in galaxies, and they are summarized below; in reality, these mechanisms are not entirely distinct because they all involve related gravitational effects, and they may even work together in many cases.

2.1 Spiral Patterns

Spiral structure has long been recognized to be capable of transporting angular momentum in galaxies, and it plays an important role in some of the simulations

that have been reported here. Two distinct physical effects are involved: (1) the gravitational torque acting between the inner and the outer part of any spiral arm transports angular momentum outward if the arm is trailing, and (2) a spiral density wave has an associated energy and angular momentum that are also transported outward by wave propagation if the spiral pattern is trailing. The energy and angular momentum of a wave in a disk are negative inside its corotation radius and positive outside it, so that if a wave is somehow generated in a disk and then dissipated, for example by shocks, the net effect will be that inner part of the disk loses energy and angular momentum while the outer part gains. The rate at which gas flows inward as a result of these effects depends on the rate at which wave energy is dissipated, and the inflow timescale is essentially the orbital period divided by the fractional energy of the gas dissipated per orbit. In normal spiral galaxies the resulting gas inflow is quite slow, and has a timescale of the order of the Hubble time; thus, while inflows driven by spiral structure may well be important for normal galactic evolution, very strong spiral wave activity is required for this effect to play an important role in the fueling of nuclear activity.

2.2 Bars

Closely related to the effect of spiral patterns is the effect of bar-like distortions in driving gas inflows in galaxies. For present purposes, a bar can be regarded as a particularly strong and open type of spiral pattern, and its effect on the dynamics of the gas in a galactic disk is similar to that of a spiral pattern but more extreme. In a barred galaxy the departure of the gas motions from circular orbits can become very large, and can cause strong shocks to form along the leading edge of the bar; this in turn can result in rapid energy dissipation and hence a strong inflow. Many presentations at this meeting have demonstrated the existence and the importance of such effects, both in numerical simulations and in observations, and have shown that the gas tends as a result to pile up in a ring with a double-peaked density distribution near the Inner Lindblad Resonance (if an ILR is present, as seems usually to be the case). This gas accumulation can then fuel star formation in a nuclear ring of ‘hot spots’, which is a common observed phenomenon in barred galaxies. The impressive agreement that has been achieved between simulations and observations of barred galaxies shows that a good understanding of their dynamics and evolution is finally being approached, at least with regard to the basic features. The gas inflow rate can be quite high when a bar first forms, but in a steady state it becomes considerably smaller and careful modeling is then required to determine it. It is clear in any case that gas inflows are much more important in barred than in unbarred galaxies, since bars are often observed to be strongly depleted of gas and star formation, both of which appear to have been moved inward to the nuclear regions of these galaxies.

While it is clear that a bar can funnel gas efficiently from the disk of a galaxy into a central region only several hundred parsecs in radius, the presence of an ILR

causes the gas to pile up at this radius and thus appears to present an obstacle to further inflow. Since the fueling of nuclear activity requires the gas to flow inward to much smaller radii, much interest has been expressed at this meeting in the question of whether similar mechanisms can also operate on smaller scales; for example, there has been much interest in the possibility that ‘bars within bars’ may form and continue to drive inflows to smaller radii. Observations of the innermost parts of some galaxies have provided evidence for the presence of separate nuclear bars or spirals, but there is as yet no clear understanding of the importance of such phenomena or of the mechanisms that might be responsible for producing them. One possibility is that mode coupling might play a role if the corotation radius of an inner bar coincides with the ILR of an outer bar. It is also possible that the self-gravity of the gas becomes very important in many galactic nuclei and contributes to the formation of nuclear bars or spirals; however, the self-gravity of the gas may also lead to other more complex phenomena, as are discussed next.

2.3 Dynamical Friction

A third possible mechanism for driving at least sporadic inflows in galaxies involves dynamical friction, which can cause massive clumps of matter to lose energy and angular momentum and sink rapidly toward the center. The timescale for the sinking of a clump toward the center is approximately its orbital period divided by the ratio of the clump mass to the total mass in the region; thus if sufficiently massive clumps are present in the inner part of a galaxy, either because they fall in from the outside or because they form there by instabilities, the evolution of the central region can become quite rapid and violent. A particularly dramatic example is provided by a merger of two galaxies, in which dynamical friction can cause the nuclei of the two galaxies to spiral rapidly together and merge. Massive clumps might also form as a result of gravitational instability in a nuclear disk or ring of gas if the self-gravity of the gas becomes sufficiently important, as might occur for example if gas is accumulated by bar-driven inflows. Several simulations of the dynamics of gas in galactic nuclei were reported at this meeting, and they show that such phenomena can have major effects, including not only the rapid sinking of massive clumps toward the center but also the occurrence of violent interactions between the clumps; massive clumps also tend to scatter stellar orbits and thus inhibit bar formation or disrupt existing bars.

The actual effects of gravitational instability of the gas in galactic nuclei remain uncertain, however, because the gas clumps that form may soon be disrupted by star formation, thus reducing the importance of dynamical friction and allowing more organized phenomena such as spiral waves or bars to play a more important role. In any event, the results of the various numerical simulations that have been reported here suggest that one type of non-axisymmetric disturbance or another may always occur and cause gas to flow inward, as long as enough gas is present; thus, given the

variety of effects that can operate, nature may always manage to find one way or another to make the gas in a galactic nucleus more centrally concentrated.

2.4 Tidal Interactions

A final mechanism that can drive rapid gas inflows in galaxies is the effect of tidal interactions, which can be especially effective because in addition to producing a perturbation in the gravitational potential similar to that of a bar, they can induce strong responses such as spiral patterns and bars in galactic disks that contribute to the outward transport of angular momentum. In the simulations of tidal encounters that were reviewed at this meeting, the most important effect appears to be the formation of strong bars in both the stellar and the gas components of a perturbed galaxy; since the gas bar tends to lead the stellar bar, it experiences a decelerating torque that causes the gas to lose angular momentum and fall rapidly inward. A substantial fraction of the gas in a galactic disk can as a result fall into the nuclear region within a short period of time. Enormous central concentrations of gas comparable to those predicted by the simulations are in fact observed in many interacting galaxies, so it seems almost certain that the energetic activity in their nuclei has been caused by tidally driven inflows from regions of galactic size. In all, the impressive degree to which current numerical simulations of interactions and mergers reproduce many of the observed properties of active galaxies provides compelling evidence for the importance of tidal effects.

3 BLACK HOLE FEEDING

All of the dynamical phenomena that have been discussed so far occur on scales of the order of a hundred parsecs or larger, and can be understood on the basis of relatively simple physics involving only Newtonian gravity and gaseous dissipation. The fueling of nuclear starbursts, which typically occur in regions a few hundred parsecs across, may thus be explainable largely on the basis of well-understood gravitational physics. It is also possible, but presently far from clear, that similar mechanisms operate on much smaller scales and play a role in the fueling of central black holes. This possibility is supported by some of the simulations presented at this meeting which have included the self-gravity of the gas in galactic nuclei and have shown that several different effects can lead to continuing gas inflows, as discussed above. However, the results of these interesting numerical experiments cannot yet be compared directly with any observations, so that their applicability to real galaxies remains unclear. Given the likely complexity of the dynamics of the gas in galactic nuclei, further progress in understanding the many processes involved will require increasingly detailed observational studies, coupled with parallel numerical work directed toward modeling the observations and clarifying the processes involved.

The mechanisms that might be responsible for driving inflows on much smaller

scales than have been discussed so far, especially scales smaller than a parsec, remain at present a matter for speculation. Accretion disk models have been considered, but they encounter some difficulties, among which is the fact that such disks are likely to be violently gravitationally unstable. A possible outcome of gravitational instability in such central gas disks is that it might lead to the formation of clumps that continue to spiral inward through dynamical friction, as discussed above. It is unclear whether this or any of the other effects that have been discussed so far could drive accretion all the way into a central black hole, although it is perhaps worth keeping in mind that it is very easy in numerical simulations of self-gravitating systems containing gas, including collapsing protogalaxies and gas-rich galactic nuclei, to end up with configurations that are as centrally condensed as is allowed by the numerical technique used.

Perhaps a more likely outcome of gravitational instability in a disk around a central black hole, as was also suggested at this meeting, is that it leads to rapid star formation, and that various feedback effects of this star formation then mediate the continuing inflow of gas into the black hole; relevant feedback effects might include the generation of turbulence and the generation of strong magnetic fields. Given the likely ionized and turbulent state of the gas near a central black hole, the generation of strong magnetic fields is perhaps inevitable, and these magnetic fields might then dominate the dynamics of the gas in the innermost region and play a major role in black hole accretion. There is evidence that strong magnetic fields are present near the centers of active galaxies (and even of our own relatively inactive galaxy), and that they play an important role in producing or collimating jet-like outflows. Again, there is a possible analogy with star formation: while protostellar accretion disks are believed to play an important role, there is evidence in many cases that these disks are truncated near the central star, and that the final step of the accretion process involves the infall of gas onto the star along magnetic field lines.

If black hole accretion is indeed driven or mediated by the feedback effects of star formation, then clearly star formation is not just an incidental accompaniment to non-thermal activity in galactic nuclei but is a necessary part of the accretion process itself. Such a causal connection between star formation and black hole accretion might provide a physical basis for the often hypothesized evolutionary connection between starburst activity and non-thermal activity in galactic nuclei, i.e. for the possible evolution of starburst nuclei into Seyfert nuclei or quasars.

4 COSMOGONICAL IMPLICATIONS

As has been noted, the processes that have been discussed play an essential role in the formation of the innermost parts of galaxies and their central black holes. Given the very general nature of the transport processes on galactic scales, which require only the presence of non-axisymmetric disturbances and gaseous dissipation, the formation of highly centrally condensed structures in galaxies seems almost inevitable.

Even the formation of massive black holes may be an almost inescapable outcome of the tendency of the gas in galactic nuclei to become ever more centrally condensed. In fact, as long as dissipation and cooling can occur, the gas in a galaxy must all eventually condense into stars or into a central black hole, or it must be expelled from the system by the energy released by these processes. All three of these possible fates for the gas apparently do occur in many galaxies, and all can play important roles in galaxy formation and evolution.

The total amount of energy released by star formation in galactic nuclei is of the same order as the amount released by black hole accretion, and this makes it difficult in most cases to argue that one or the other of these sources is dominant. However, black hole accretion is about two orders of magnitude more efficient than star formation in converting mass into energy, and this means that the most luminous active galaxies are almost certainly powered mainly by black hole accretion, since star formation cannot generate enough energy to account for their luminosities from the mass present in the small region from which the luminosity is emitted. The fact that black holes only need to accrete about one percent as much mass as goes into stars in order to liberate comparable amounts of energy may help to explain why black holes account for roughly only one percent of the mass in the inner regions of galaxies: such a limit on their masses might result if black hole accretion is driven by the feedback effects of star formation, but its rate is limited by the condition that the energy released cannot greatly exceed the energy released by star formation, since otherwise the remaining gas might be blown away rather than accreted.

From a cosmic perspective, most of the phenomena that have been discussed at this meeting can be viewed as various aspects or consequences of the inexorable tendency of some part of the gas in the universe to become ever more condensed, while the energy released causes the remaining gas to become more dispersed. Thus, the processes of galaxy formation, galaxy interactions and mergers, bar and spiral dynamics, gas inflows, gravitational instabilities, star formation, magnetic field generation, black hole accretion, jet formation, etc., that have been discussed here can all be seen as playing significant roles in the evolution of the matter distribution in the universe into both more condensed and more diffuse forms, with the consequent release of energy in the densest regions that is responsible for the most spectacular observed cosmic phenomena.