STAR FORMATION AND DYNAMICS IN STARBURST NUCLEI

COLIN A. NORMAN
Department of Physics and Astronomy, Johns Hopkins University and
Space Telescope Science Institute,
Baltimore, Maryland 21218

ABSTRACT

A simple model is presented for gas inflow through a disk galaxy driven by interacting galaxies through the action of a non-axisymmetric disturbance acting on the disk whose gas is modelled as an ensemble of gas clouds. Cloud collisions, as well as being a vital process in forcing gas inflow to the centre of the disk, are also assumed to generate massive stars. This ever increasing rate of gas flow toward the centre of the galaxy and the associated rapid increase in cloud collisions leads to a centrally concentrated starburst.

Starbursts have important consequences for the immediate environment of galaxies. Mildly collimated outflows can be driven by a combination of multiple supernovae and OB star winds. Jets associated with activity in the galactic nucleus can interact strongly with a starburst environment.

Physical mechanisms proposed for generating starbursts and active nuclei via feeding the monster are rather similar and a strong inference is that starbursts and activity are intimately related. Among the obvious evolutionary implications are that powerful infrared sources could be forming a significant part of their central stellar mass--which is galaxy formation in action--a relatively delayed and hidden process. Furthermore, quasar-like nuclei embedded in such objects as Arp 220 will be powerful infrared sources until the gas and dust is depleted either by ejection and/or by transformation to stars.

I. INTRODUCTION

The remarkable observations of starburst systems discussed at this meeting require at least some theoretical modelling. The analysis I discuss here is quite simplified but may lead to some more physical insight. It will be assumed that it is necessary to explain why companions and mergers trigger starbursts, what skews the mass functions to predominantly OB stars in these systems, what drives the observed outflows, what is the relation between activity and starbursts? In addition we will discuss the implications of the infrared observations for theories of galaxy formation and quasar activity and for the metal enrichment of the intracluster medium.

II. INTERACTION DRIVEN INFLOW

Consider a normal disk galaxy with a significant gas content, say an Sc galaxy, and apply a significant perturbation to it in the form of a companion, bar, oval distortion or infalling or merging dwarf galaxy. Assume the pre-

existing stars provide a background potential and that the gas distribution is described as a mean cloud ensemble that can undergo various dissipative processes such as collisions, coagulation, disruption, fragmentation etc. To illustrate the relevant physics here we will simplify this system further by assuming the perturbation is a linear (~10%) non-axisymmetric distortion, cloud orbits can be described as test particles with drag and cloud collisions are the sources of the drag as well as providing the massive star formation mode.

The technique used to calculate the response is to follow the elegant stellar dynamical formulation of this problem by Lynden-Bell and Kalnajs (1971) and butcher it by adding a collisional drag component to some of the stars that are then called clouds. The general linear non-axisymmetric distortion is Fourier decomposed into spiral modes, a transformation is made to action angle variables, it is assumed the dominant collisional damping is on the radial action and the long wavelength limit is taken. The rate of change of angular momentum at any given radius in the disk is given by

$$\langle \dot{h} \rangle = \frac{2\gamma \, m^2 \, k^2 S^2 (\Omega - \Omega_p)}{\left(m(\Omega + \Omega_p - \frac{K}{m})^2 + \gamma^2 \right) \left(m(\Omega + \Omega_p + \frac{K}{m})^2 + \gamma^2 \right)} \tag{1}$$

where S is the potential wave amplitude, k is its radial wave number, γ is the drag collisional rate, Ω in the rotation frequency of the disk, Ω_p is the wave pattern speed, K is the epicyclic frequency and m is the number of arms associated with the perturbation (Norman 1984). The change of sign of the effect at corotation when $\Omega = \Omega_p$ is obvious, as is the crucial dependence of $\langle \dot{h} \rangle$ on the presence of **both** the cloud collisions and the presence of the perturbing wave. Physically, the clouds lead to the bar or general wave perturbation inside corotation by an angle that is of order γ. This is just the forced oscillator with drag response problem, where the drag gives a phase shift. These leading clouds form a system that is torqued down by the action of the corresponding stellar bar thus losing angular momentum and having the clouds move inwards. Outside corotation the clouds move outwards since the effect changes sign. This simple analysis fits the numerical simulations done by Schwarz (1981) and Combes and Gerin (1985). Away from resonances, which is the general case, the inflow velocities can be written, at radius R,

$$v_r \sim 2\gamma \, m^2 R \, [kR]^2 \left[\frac{S^2}{\Omega^2 R^2} \right] \left[\frac{\Omega - \Omega_p}{\Omega} \right] \tag{2}$$

for $k \neq 0$, and for $k = 0$

$$v_r \sim 2\gamma \, m^2 R \left[\frac{S^2}{\Omega^2 R_h^2} \right] \left[\frac{\Omega - \Omega_p}{\Omega} \right] \tag{3}$$

Once again we see that the combination of enhanced cloud collisions and large amplitude perturbations will give greatly enhanced inflow. To estimate timescales we need to establish the nature of the drag. There are two cases here. If the drag is due to collisions with background clouds the inflow velocity will increase exponentially with time as $e^{t/\tau}$, and secondly if the drag is due to collision with other large clouds the temporal behaviour will be as $(1 - t/\tau)^{-1}$. The timescale $\tau = 1/\gamma$ is obtained from a $[n_{cl} \, \sigma_{cl} \, v_{cl}]^{-1}$

estimate and here taking quantities relevant to the central region of ARP 220 we find a timescale of 2×10^7 yr, and for a normal Sc $\sim 10^9$ yr, when in both cases a wave perturbation of order $\sim 10\%$ is assumed. Thus the mechanism is efficient and roughly fits even the rapid inflow rates required for starbursts. For Arp 220 there are also interesting implications for star formation and the details of the estimate for τ are found in the following section.

III. STAR FORMATION IN STARBURSTS

The question here is what is the physical process that skews the mass function to high mass only?? Theories are very ambiguous here. For example, in another high pressure environment such as a cooling flow it supposed that only low mass stars form. Low mass star formation may be inhibited by shear, turbulence or magnetic fields but may is the relevant word here. The approach I will take here is to base the model on powerful observationally based arguments presented by Scoville (this meeting) that cloud-cloud collisions generate massive OB stars, and by clouds it is generally meant molecular clouds. Taking relevant parameters for Arp 220 to be 10^{10} $M_\odot$ of gas in the inner 3 kpc and assuming 10^5 $M_\odot$ per cloud and a cloud radius of 5 pc and a velocity dispersion of 20 km s^{-1} and a wave amplitude of 10% and a star formation efficiency of $\sim 10\%$ we get $\tau \sim 2 \times 10^7$ years in the previous section and a rate of OB star formation of $\sim 10^2$ OB stars per year!

Cloud collisions rates can be significantly enhanced by the presence of bars and ovals that generate shocks and give substantial orbit crossings. In the central regions of triaxial systems there are many box orbits that have plunging radial trajectories with the possibility for much orbit crossing. In systems with strong central mass concentrations stochastic orbits can develop and these orbits wander stochastically around the central region greatly increasing the collision rate. This effect will be very significant for ratios of black holes (in other central mass concentrations) to core masses of order 10^{-3} to 10^{-1} (Norman and May 1984).

IV. OUTFLOWS FROM STARBURSTS

Outflows from starbursts systems seem ubiquitous (Heckman, these proceedings). The mechanical energy and momentum input is clearly very substantial. For a supernova rate of 1-10 yr^{-1} one finds a luminosity $L \sim \eta$ 10^{43} erg s^{-1} in an outflow where η is an efficiency factor. There are several ways to model these outflows. Chevalier and Clegg (1985) have given a spherical wind model with a wind velocity of order $V_w \sim 2000$ km s^{-1} at 200 pc and a terminal cloud velocity of $V_t \sim 400 \, [(10^{21} \, cm^{-2})/(Ncl)]^{1/2}$ km s^{-1}. The x-ray emitting gas is produced by shocked clouds and filaments in the wind itself. Wind or explosion driven shell propagation and evolution has been studied by various authors (c.f. Sakashita and Hanami 1986, Norman 1986 plus references). A mild, wide-angled collimation of order 30-40° is found and various evolutionary sequences can be seen as the shell is embedded in and bursts out of the disk. These various stages can be compared with the data (Heckman, Sofue, this conference). In the final state we expect a steady state wind propagating in a core between two shock waves at the long edge of the core and a massive molecular ring in the disk at the boundaries of the outflow

region. The opening angle of the core is of order the inverse Mach number of the flow at one disk scale height. Shocked clouds, bullets and filaments will give the coronal x-rays and optical lines. Molecular lines may well be observed in these outflows. The Galactic Centre itself has many of these properties (Pudritz, Norman and Heyvaerts 1986) if associated with a relatively small starburst $\sim 10^7 - 10^8$ years ago.

The metallicity content of these outflows is rather interesting. A supernova rate of 1-10 supernovae per year producing approximately 1 $M_\odot$ of iron per supernova over a burst lifetime of $\sim 10^8$ years gives an injected iron mass of $10^8 - 10^9$ $M_\odot$ of Fe into the intracluster or intergalactic medium. We assume the gas does not cool and supernovae bubbles intersect before significant cooling at such high supernovae remnant densities found in starburst systems. This is a very significant metallicity input to the intra cluster or intergalactic medium. One needs of order greater than 10^{10-11} $M_\odot$ of processed material per luminous L_* galaxy injected into the intracluster medium (Henriksen 1985) to explain the metallicity of the intracluster medium. If the starburst outflow were ubiquitous in the early stages of cluster evolution this could solve the metallicity of clusters problem, essentially due to the distorted initial mass function of starbursts.

IV. ACTIVITY AND STARBURSTS

There are many ways in which starbursts and activity can be related and here I will briefly note a few of these. Jets can certainly trigger star formation as is discussed in the context of Minkowski's object by van Bruegel et al (1985) and Centaurus A (de Young 1981). Jet pressures are high compared to interstellar medium pressures

$$P_{jet} \sim 10^{-9} \left(\frac{L_{jet}}{10^{42} \text{ ergs}^{-1}}\right) \left(\frac{(100 \text{ pc})^2}{A_{jet}}\right) \left(\frac{10^4 \text{ km s}^{-1}}{v_{jet}}\right) \text{ dyne cm}^{-2} \qquad (4)$$

where L_{jet}, A_{jet} and v_{jet} are the jet luminosity, shear and velocity. The over pressure induced by a jet striking a cloud is very similar to the effect of a cloud-cloud collision and can therefore probably trigger massive OB star formation. In this picture clouds can either orbit into a jet or be struck by a jet propagating through the interstellar medium.

The structure of the molecular clouds and the interstellar medium can be significantly affected by the prescence of activity. For example the ionization balance in molecular clouds in the central region can be changed by more than an order of magnitude if a powerful central x-ray source is present. This can substantially lengthen the ambipolar diffusion time and possibly lead to more massive star formation (Silk and Norman 1983).

The presence of starbursts can feed the monster creating the active nucleus. Massive OB stars on radial box orbits or stochastic orbits can plunge toward the central black hole and accretion disk on timescales of order a core crossing time which is less than the time to evolve to a supernova. Thus high pressure and other direct mass injection processes can occur due to the action of starburst generated supernovae exploding near the central object. More generally, the processes discussed here for fuelling starbursts are the same as

those for fuelling quasars. Recall that for powerful quasars one needs 10-100 $M_\odot$ yr^{-1} and, conversely, it is difficult to see how such prodigious mass inflows could avoid forming stars!

V. SUMMARY

A model has been presented where the action of a companion on a gas-rich spiral galaxy can induce mass inflow rates typical of those required for Arp 220 and a starburst rate of massive OB star formation of ~10-10^2 per year where it is assumed cloud collisons trigger the massive star formation mode.

Supernovae and OB star wind driven outflows were discussed and various evolutionary stages were noted. The outflows would be significantly metal enhanced and could provide the major source of metals to the intracluster medium.

Starbursts and activity are intimately related--it is difficult to conceive of one without the other in massive gas rich system with central black holes. Massive starbursters appear to be forming a significant fraction of their central stellar mass. This is indeed galaxy formation by any other name. The process is apparently hidden by dust and occurs in bursts! Any quasar embedded in such a system would be quite successfully shrouded until the dust is removed. Arp 220 seems an excellent example. These points learned from the infrared work must be kept in mind when discussing both galaxy formation and quasar evolution.

REFERENCES

Chevalier, R. A. and Clegg, A. W. 1985, Nature, 317, 44.
Combes, F. and Gerin, M. 1985, Astron. Astrophys., 150, 327.
DeYoung, D. S. 1981, Nature, 293, 43.
Heckman, T. 1986 (these proceedings).
Henriksen, M. 1985, Ph.D. thesis, Univ. of Maryland.
Lynden-Bell, D. and Kalnajs, A. 1972 M.N.R.A.S., 157, 1.
Norman, C. and May, A. 1984, unpublished.
Norman, C. 1984, in Formation and Evolution of Galaxies, ed. J. Audouze and J. Tran Vanh 1984, D. Reidel, p. 327.
Norman, C. 1986, IAU, 116, in press.
Pudritz, R., Norman, C. and Heyvaerts, J. 1986, in preparation.
Sakashita, S. and Hanami, H. 1986, PASJ, in press.
Schwarz, M. P. 1981, Ap. J., 247, 77.
Scoville, N. 1986 (these proceedings).
Silk, J. and Norman, C. 1983, Ap. J. Letters, 272, L49.
Sofue, I. 1986, these proceedings.
van Breugel, W., Filippenko, A. V., Heckman, T. and Miley, G. 1985, Ap. J., 293, 83.

DISCUSSION

SCOVILLE:

The size of 3 kpc assumed for the gas distribution in Arp 220 is consistent with the new Owens Valley Interferometer maps of the CO as will be presented by Anneila Sargent tomorrow.

NORMAN:

Sounds good to me!

BURBIDGE:

You say that with a black hole and a starburst all of the phenomena can be explained. But how about a prediction? Which comes first, and how do these systems evolve?

NORMAN:

Good question. I have tried to answer this in the text.