SPACE TELESCOPE SCIENCE INSTITUTE

PREPRINT SERIES
No. 190

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August 1987

SPACE TELESCOPE SCIENCE INSTITUTE
Homewood Campus Baltimore, MD 21218

Operated by the Association of Universities for Research in Astronomy, Inc., for the National Aeronautics and Space Administration

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To appear in the proceedings of the Moriond Conference on

Star Formation in Galaxies, eds., T. X. Thuar and T. Montmerle

December 1988

ABSTRACT

Detailed mechanisms associated with dynamical process occurring in starburst galaxies are considered including the role of bars, waves, mergers, sinking satellites, self-gravitating gas and bulge heating. Our current understanding of starburst galaxies both observational and theoretical is placed in the context of theories of galaxy formations, Hubble sequence evolution, starbursts and activity, and the nature of quasar absorption lines.

1. INTRODUCTION

Starburst systems are dynamically very interesting. In the low luminosity range we find turbulent, chaotic motions of stars and gas in dwarf galaxies, in barred galaxies the starburst mode is enhanced by about a factor of two and in the powerful infrared starburst galaxies, interactions between galaxies appear to be an obvious driving force behind the burst mode. Over this vast range of luminosities there are some quite elementary considerations of a dynamical nature that may clarify some of the physics. The physics of starburst systems can be made as complex as one wishes and the focus here on dynamical processes is obviously for the sake of clarity and at the expense of completeness. We do not yet know if there is one specific starburst mechanism. In fact, I shall assume the contrary and set out the various possibilities. Angular momentum transport by bars and spiral waves are treated, outlining the essential processes associated with any such non-axisymmetric distrubance in a dissipative medium. The central point is that outside corotation gas will flow outward to the outer Lindblad Resonance and inside corotation it will flow inwards to the inner Lindblad Resonance(s) or the nucleus, in the absence of this latter resonance. The effects of interaction are treated by analysing the effects of mergers which are clearly appropriate to the powerful sources and in the somewhat more intermediate cases we use results from work on sinking satellites. Here it is obvious that a satellite galaxy can readily reach the centre of an L_* galaxy but in doing so, considerable disk damage may result. A few remarks are made here on how flat disk-like system may in fact become bulges.

In the central regions of objects such as Arp 220 the starburst mode is so strong that a significant fraction of the central bulge is being turned into stars. This logically leads us into considerations of galaxy formation from the starburst point of view, evolution of galaxies along the Hubble sequence, the relation between starbursts and activity, and the nature of quasar absorption lines that may be associated with the environments of starburst system and their huge bipolar outflows. For very interesting considerations of the nature of the interstellar medium and the actual details of the star formation process one should study the contributions to this volume by Ikeuchi and Larson. What help do we have other than studying starbursts in our quest for a serious theory of galaxy formation? One very interesting approach we can take is to assume that we have actually *seen* the protogalaxies. Protospirals we associate with the damped Lyman alpha system seen by Wolfe and colleagues (Wolfe *et al.* 1986). These systems have column densities of $\sim 10^{22}$ cm^{-2} and cover 20% of the sky at a redshift of 2–3. The estimated mass density of the system is sufficient to account for all the luminous matter in the universe within a factor of 2. Protoellipticals would be the objects found by Djorgovskii, Spinrad and others (Djorgovskii *et al.* 1987) by deep imaging with filters of emission line regions around distant 3CR sources. Quite possibly these could be merging protospirals producing elliptical galaxies and initiating the triggering of an active nucleus. One interesting point here is that the radio axis appears to be aligned with the axis of emission-line gas whereas at low redshift it is, in fact, orthogonal (Chambers *et al.* 1987). Evolutionary tracks of galaxies may eventually be calculable and even at this very early stage it is worthwhile to think of galaxies evolving in some parameter space. This image is clear enough but what is the best parameter space in which to think of this evolution. The classic Hubble sequence is that of bulge to disk. According to Sandage (1983) "anyone who has looked through a telescope" would clearly classify galaxies according to the surface brightness of the bulge. The total luminosity of the bulge gives a one parameter fairly for the Hubble sequence as outlined by Meisels and Ostriker (1984). Recent studies of elliptical galaxies (Davies *et al.* 1987) and spiral galaxy bulges (Dressler 1987) show that some of the fundamental parameters are constrained to lie on a plane that is similar for both elliptical and bulges (of early type galaxies). The essential physics here is that binding energy increases with mass. The larger system are more tightly bond with respect to the virial theorem. Does this then mean that larger systems have dissipated more (Djorgovskii 1986)? Even though we don't have details about the hyper-plane along which galaxies evolve we will crudely assume it exists and we hypothesize that we may learn much about the speed and trajectory on this hyper plane from studying starburst systems.

2. WAVES AND BARS IN GAS-RICH DISKS

Conventional stellar bars driving gas flows generate rapid inflow near the bar. The nature of the periodic orbits changes near resonances and this sharp change cannot be achieved by the gas and shocks develop driving further flow inwards. Spiral waves, which can, in reality, be dominated by the self gravity of the gas, produce a more gradual outflow than a bar. There resonances can damp the waves and thus inhibit the inflow. For purely stellar supported waves they are absorbed at the Inner Lindblad Resonance. We further note that a rapid rise of $\sigma(r)$ towards the centre reflects the wave. As shown by Lubow (1987), a five percent ratio of gas to stars results in effective Q parameters both for the stars and gas of comparable amplitude due to the low temperature and scale height of the dissipative gas layer. At a ratio of 15% the gas dominates the wave self gravity by nearly an order of magnitude. Modelling the central disk of NGC 1068 the wave surface density increases as $r^{-\alpha}$, with $\alpha \sim 3/2$ and this *strong* increase towards the centre can result in a strong central concentration of shocks and star formation. This is most interesting. Starbursts seem to occur more frequently in later type systems with gas rich disks and there is clearly some strong wave driving by, for example, a companion. Is the feedback positive or negative? The wave amplitude can be self limited due to cloud collisions. This negative feedback situation can probably be overcome and turned into a positive feedback starburst situation by sufficiently increasing the angular momentum flow rate so that the gas inflow rate $\dot{M}$ is high enough to overcome this. There is a possibility here of a natural threshold, due to say cloud-cloud collisions, that is to be overcome so that the mode is that of a *burst*. As discussed previously Norman (1987) we consider a disk with an ensemble of clouds and a general non-axisymmetric perturber. Cloud collisions are analysed as straight $\langle n\sigma v\rangle$ collisions to give a collision rate γ. Following a straightforward analysis derived as a dissipative version of Lynden-Bell and Kalnajs we find the angular momentum flow rate is

$$\dot{h} = 2m^2\gamma k^2 S^2(\Omega - \Omega p)/\Omega^4$$

with characteristic time scale of inflow

$$\tau^{-1} = \dot{h}/h = 2\gamma m^2 \left[\frac{S}{\Omega^2 R_h^2}\right]^2 \left[\frac{\Omega - \Omega p}{\Omega}\right] (kR_h)^2$$

Away from resonances, the wave-driven viscosity will beat the ordinary collisional viscosity ($\nu \sim \frac{1}{3}\ell v$) if the wave amplitude is greater than

$$\left(\frac{S}{\Omega^2 R_h^2}\right) > \frac{1}{\sqrt{3}m(n\sigma R_n)} \approx \frac{\ell}{\sqrt{3}mR_h}$$
$$\gtrsim 3\%$$

where $\ell/R_h \sim h/R_h \sim 0.1$ and $m = 2$. The combination of enhanced cloud collision and large amplitude perturbations can give very greatly enhanced inflow by at least an order of magnitude.

Using standard $n\sigma v$ estimates with wave amplitudes of order 10% we find an inflow timescale for the centre of Arp 220 of $\approx 2 \times 10^7$ year and for a normal Sa galaxy of $\gtrsim 10^9$ years. There are many ideas of what actually gives the mass function but let us calculate here the interesting possibility that it is cloud-cloud collisions (Scoville 1986). Using numbers from Arp 220 from (Scoville *et al.* 1986a) we divide the 10^{10} $M_\odot$ of gas in the central region ($\lesssim 3$ kpc) of Arp 220 with 10^5 objects of 10^5 $M_\odot$ with radius of 5 pc and velocity dispersion of 20 km s^{-1}! Assuming a star formation efficiency of $\sim$ 10%, the stars formation rate becomes 10^2 OB star per year.

Bars exhibit a strongly non-linear gas response and it is necessary to perform detailed numerical calculations to obtain precise estimates. The time scale for gas inflow is of order $\sim (3 - 10)\tau_{rot}$. Larson (1985) has estimated the time scale to be $\tau \sim m\tau_{rot}(M_{halo}/M_{disk})(\delta\Sigma_d/\Sigma_d)^{-2}$ and for a general wave with pitch angle j he has estimated a timescale $\tau \sim m(\Sigma_d/G(\delta\Sigma_d)^2)(V_{rot}/\sin j \cos j)$ which both give estimates of time scales similar to those made above.

3. SELF-GRAVITATING GAS IN CENTRAL REGIONS

Masses of molecular gas such as these inferred from the CO observations of starburst galaxies show that the central potential well may, in fact, be dominated by the gas itself or at least very significantly affected. For such systems the condition for instability to form a massive bar in the gas itself is $T/W \lesssim 0.14$ (Ostriker and Peebles 1973) that depends in detail on the actual mass distribution. This will give a very rapid transfer of angular momentum by, for example, interaction with the halo. The timescale for decay or slow down of such a bar and consequent mass inflow is short.

$$\tau_{decay} \sim 10^1 - 10^{1.5}\tau_{rot}(M_{bar}/M_{halo})$$

including the effect of strong shocks and dynamical friction giving

$$\tau_{decay} \sim 3 \times 10^6 - 10^7\ yr$$

on scale of order ~ 1 kpc. It is therefore very important to map the central regions in CO with submillimetre interferometers to accurately establish the mass distribution in the gas and to search for linear offset shocks as indication of the presence of barred galaxies.

A most interesting effect due to such a massive central concentration of molecular clouds is the enhanced two-body star cloud heating rate whereby stars are heated by "collisions" with clouds. The velocity dispersion obtained by stars in, say, the centre of Arp 220 is

$$\sigma \approx 160 \left(\frac{\sigma_{d,gas}}{10^5 \ M_\odot \ pc^{-2}} \right)^{1/4} \left(\frac{t}{10^8 yr} \right)^{1/4} km \ s^{-1}.$$

Thus a significant number of metal-rich population II stars can be heated to form a bulge in, of order the lifetime of the starburst $\sim 10^8$ yr. This is quite possibly relevant to the very metal-rich halo stars in our Galactic Bulge found by Whitford and Rich (1986), the formation of very thick inner disks and once again the possibility of evolution along the Hubble Sequence.

In the spherical case of a gas rich dwarf galaxy, protoelliptical galaxy, or the central region of a star bursting bulge we have a novel cooling flow problem with a pressure loaded polytrope of cooling molecular gas. Massive accretion $\dot{M} \sim 10 - 100 \ M_\odot \ \mathrm{yr}^{-1}$ can occur, as will massive star formation and self regulation of the accretion can occur due to the energy input from star formation.

The cloud-cloud collision rate is considerably enhanced by orbit crossing. In triaxial systems the box orbits can cross and if gas is following these orbits they will suffer very enhanced dissipation (Lake and Norman 1983). If a black hole is grown in the central region of galaxies the orbits will go from being regular box orbits to stochastic orbits to regular tube orbits. Norman and May (1985) found that for a hole to core mass ratio of 10^{-3} to 10^{-1} the orbits in a dominant nuclear bar will be predominantly stochastic.

4. INTERACTION OF DISKS WITH GAS-RICH DWARFS/COMPANIONS

Spiral galaxies are very responsive to satellites and consequently can trap them into merging on short time scales. Their fate is to reach to the central bulge regions on a time scale estimated by Quinn and Goodman (1986) to be

$$\tau_{sink} \sim 4 \times 10^9 \left(\frac{10^9 \ M_\odot}{M_{satellite}} \right) \left(\frac{v_c}{220 \ km \ s^{-1}} \right) \left(\frac{r_c}{10kpc} \right)^2 \left(\frac{3}{\ln \Lambda} \right) yr$$

This is a very crude estimate since the interplay of effects here is very subtle— dynamical friction, resonance effects and horseshoe orbits. Sometimes even the sign is difficult to ascertain! The normal descent of a satellite is a damped vertical oscillation to the plane and then a radially inward motion to the nucleus. Very considerable damage is done to the disks during this process and the morphology of the underlying galaxies shows the signature of this essential process occurring. Here, once again, the issues of bulge building, disk heating, starbursts and activity, damaged galaxies and Hubble sequence evolution are all intertwined. There are certainly not obviously enough gas rich satellites to produce all the active and starburst systems that we see. These basic fuel units may however have been much more numerous in the past and associated with quasar absorption lines (c.f.

Silk and Norman 1981, Ikeuchi and Norman 1987). However, at the current epoch it may be that merging generates bridges and tails which then form break up into small, cold (i.e. low velocity dispersion) objects in the potential well of the merged system and which then form such satellites as described above.

As cosmological simulations have shown (c.f. Roos and Norman 1979) merging occurs mainly in broad sub clumps. The relative velocity of merging galaxies must be less than their internal velocity dispersion, i.e. $v_{rel} \lesssim 1.1\sigma_{gal}$. The process of violent relaxation occur during merging since $\Delta U/U \sim 1$ where U is the internal energy of the galaxy. Assume that the interstellar media of the two galaxies are, as is usual, dominated by a multi-phase medium with a cool dense component in the form of massive clouds. Elliptical galaxies will be produced when $n_{cl}\sigma_{cl}v_{cl}t_{cross} \sim$ few, and the end result will be a spiral galaxy when the value of $n_{cl}\sigma_{cl}v_{cl}t_{cross} \gg 1$ and a slow settling occurs. The first possibility gives huge initial bursts of star formation of order $(10^{10}\ M_{\odot}/t_{cross}) \approx 10\ M_{\odot}\ \mathrm{yr}^{-1}$ and the second is the most likely for a regular starburst mode. In this content it is interesting to look at Sandage's (1986) recent galaxy formation proposal in a new light *not* of the rate of star formation but the value of $n_{cl}\sigma_{cl}v_{cl}t_{cross} \gg 1$. To form galaxies this way the merging must be normally that of protogalaxies. Stellar merging only is impossible. The merging of gas rich proto galaxies is crucial. As discussed extensively by Silk and Norman (1981), the galaxies must consist of bound subclumps since one needs the properties of both the ballistic orbits to maintain the triaxiality and the dissipative collisions to generate the binding energy and such features as colour gradients.

5. GALAXY EVOLUTION AND ACTIVITY

A major theme of current theoretical astrophysics is to achieve a better understanding of the Hubble sequence and of the evolution of galaxies in that classification scheme. Satellite interactions with say Sc gas rich disks can act to grow the bulge at the expense of the depletion of the satellite population and the significant heating even damage of the disk possibly to form a thick disk. Elliptical galaxies are found in more spectacular mergers of spiral protogalaxies. The rate of evolution along the Hubble sequence is given by

$$\frac{M_{int}}{t_{int}} \approx \dot{M}_{bulge}$$

corresponding to an increase in the bulge to disk ratio. From careful study of current starbursts and those accessible to the Hubble Space Telescope at redshifts greater than unity much can be learned from the observation of the milder form of the galaxy formation process at the present epoch, that occurs in a more dramatic form at redshifts of, say, 5.

Starbursts giving bulge building will probably naturally give growth of a central mass concentration such as a black hole and its associated star cluster. Scoville and Norman (1987) have shown how even the long standing problem of the nature of the broad emission line region of active galaxies and quasars can be realised in such a scenario. Most of the mechanisms for fuelling and triggering activity are similar to those invoked here concerning the driving of the starburst mechanism namely bars, orbit scattering, waves in the dissipative gascons component, massive cloud, supernovae near black holes and accretion disk around black holes, etc. Very efficient star formation in dense clouds with box-orbits are expected in star bursts. There is a big advantage for massive dense, bound star clusters that may be found in star bursts. These can rapidly spiral into the central regions on a timescale $\bar{\tau} \sim t_{dyn}\ (M_{core}/M_{cluster})$. Tidal disruption can occur *but* the fuel can be carried much closer to the centre. This process could be greatly enhanced by collapse.

Huge collinated outflows of momentum and energy from an active nucleus can trigger star formation in the surrounding medium. This is seen to happen in M51, NGC 1068, Minkowski's object, and Centaurus-A. One way to view this is to calculate the increased pressure that a cloud feels when shocked by a jet or when it orbits into a jet. The conventional pressure in the interstellar medium is $P_{ism} \sim 10^{-12}$ dyne cm^{-2} whereas the pressure in a jet at ≈ 100 pc is

$$P_{jet} \sim 10^{-9}\left(\frac{L_{jet}}{N^{12} ergs^{-1}}\right)\left(\frac{(100pc)^2}{A}\right)\left(\frac{10^4 kms^{-1}}{v_{jet}}\right) dyne\ cm^{-2} \gg P_{ism}.$$

Such an increase in pressure is similar to the effects of a cloud-cloud collision. Clouds orbiting into a jet will be triggered just as massive OB stars appear to be triggered in spiral arcs. Similarly ageing effects should be seen as newly formed stars move away from the triggered jet, just as for the spiral wave case.

The active nucleus itself can significantly affect the interstellar medium. The ionisation balance in clouds can change by an order of magnitude due to the strong X-ray radiation bathing the molecular clouds. This directly lengthens the ambipolar diffusion time since it is proportional to the ionisation balance.

Starbursts themselves can directly feed the monster. Massive OB stars on radial, chaotic or box orbits can have lifetimes to supernova τ_{SN}, significantly less than the crossing time. Thus high pressures and strong momentum inputs can be derived from nuclear supernovae. Since all the mechanisms for triggering and fuelling a starburst are the same as those envisaged for active galaxies and quasars and furthermore the mass supply rates are of order $10^2\ M_\odot$ yr^{-1} it seems hard to avoid inducing activity in a starburst nucleus.

6. QUASAR ABSORPTION LINES

Metallic quasar absorption lines are *not* like the halo of our own Galaxy (Danly, Blades and Norman 1987). What are they? They could well be star burst systems. York *et al.* (1987) have argued that dwarf galaxies could account for *some* of the systems. However, a more likely possibility considered here is that they are associated with the huge bipolar outflows found by Heckman *et al.* (1987). These are systems with large covering factors (linear extents out to $\sim 10^2$ kpc), low ionisation, low temperature, filamentary strucure, metal rich, created at the epoch of significant star formation and undoubtedly more common at the epoch of both galaxy and active galaxy formation, say, a redshift $z \sim 5$.

7. SUMMARY AND CONCLUSIONS

Bars, waves and interactions can certainly drive an outward angular momentum flow and inward mass flow. In gas-rich systems there is an interesting threshold effect below which a negative feedback effect is operating to saturate the wave amplitude and above which a positive feedback effect is possible that drives an ever increasing mass flux. The star formation processes are associated with cloud-cloud collisions or some other dissipative process in the gaseous component of the disk.

The starburst phenomenon may well allow us to understand phenomenon seen at high redshift quite possible associated with protogalaxies namely the damped Lyman alpha disks (Wolfe *et al.* 1986), highly disturbed star forming 3CR sources observed in emission lines by Djorgovskii *et al.* (1987) and features of quasar absorption lines associated with, say, gas-rich dwarfs.

Starburst theory and observation allows a deeper understanding of the evolution along the Hubble sequence particularly with respect to bulge formation, mass and angular momentum flow, flux of gas into stars and the expulsion of metal-rich material into the environments of galaxies. Activity of a galactic nucleus and starbursts are intimately associated.

An interesting observational question is what are post starburst system really like? Is bulge building really occuring in some system at the current epoch? The two central theoretical questions that have been addressed here are what are the fundamental parameters associated with the Hubble sequence and how would one go about computing tracks and secondly how this work does in fact tie in with all our current thinking on galaxy formation, the nature of quasar absorption line and the understanding of the intergalactic medium.

It is a pleasure to thank the organiser of the Moriond conference for such a stimulating gathering and for the participants for interesting discussions and encouragement in particular S. Ikeuchi, R. Larson, and B. Pagel.

REFERENCES

Chambers, K., Miley, G. and van Breugel, W. 1987, preprint.

Danly, L., Blades, C. and Norman, C. 1987, preprint.

Davies, R. L., Burstein, D., Dressler, A., Faber, S. M., Lynden-Bell, D., Terlevich, R., Wegner, G. in Proceedings of IAU Symposium *124* on *Observational Cosmology*, ed. G. R. Burbidge, and A. Hewitt (Dordrecht, Reidel), 1987.

Djorgovskii, 1986, Ph.D. Thesis, University of California, Berkeley.

Djorgovskii, S., Spinrad, H., Pedelty, J., Rudnick, L. and Stockton, A. 1987, preprint.

Dressler, A. 1987, preprint.

Heckman, T. M., Armus, L. and Miley, G. K. 1987, *A. J.*, **92**, 277.

Lake, G. and Norman, C. 1983, *Ap. J.*, **270**, 51.

Larson, R. B. 1985, *M.N.R.A.S.*, **214**, 379.

Lubow, S. 1987, in preparation.

Lynden-Bell, D. and Kalnajs, A. 1971, *M.N.R.A.S.*, **157**, 1.

Meisels, A. and Ostriker, J. P. 1984, *A. J.*, **89**, 1451.

Norman, C. and May, A. 1985, unpublished.

Norman, C. A. 1987, preprint.

Ostriker, J. P. and Peebles, P. J. E. 1973, *Ap. J.*, **186**, 467.

Quinn, P. J. and Goodman, J. 1986, *Ap. J.*, **309**, 472.

Roos, N. and Norman, C. 1979, *Astr. Ap.*, **76**, 75.

Sandage, A., 1983 in Internal Kinematics and Dynamics of Galaxies IAU *100*, p. 367, ed. E. Athanassoula.

Sandage, A. 1986, *Astr. Ap.*, **161**, 89.

Scoville, N. Z., Sanders, D. B., Sargent, A. I., Soifer, S. L. 1986a, *Ap. J. (Letters)*, **311**, L47.

Scoville, N. Z., Sanders, D. B., Clemens, D. P. 1986b, *Ap. J. (Letters)*, **310**, L77.

Scoville, N. Z. and Norman, C. A. 1987, in preparation.

Silk, J. and Norman, C. 1981, *Ap. J.*, **247**, 59.

Wolfe, A., Turnshek, D., Smith, H. E. and Cohen, R. D. 1986 *Ap. J. Suppl.*, **61**, 249.

York, D. G., Dopita, M., Green, R. and Bechtold, J. 1986, *Ap. J.*, **311**, 610.