STAR FORMATION AND GALAXY INTERACTIONS

William C. Keel
Department of Physics and Astronomy
Box 870324, University of Alabama
Tuscaloosa, AL 35487, U.S.A.

ABSTRACT. Surveys at a variety of wavelengths indicate that galaxy interactions are statistically linked to enhanced rates of star formation. The distributions of star-formation rate (SFR) show typical increases of order 30%, and only a few systems undergoing the order-of-magnitude enhancements typical of strong starbursts (particularly in mergers). Potential advantages and problems of various measures of SFR are discussed, along with issues of sample selection and comparison. Finally, various proposed mechanisms for enhancing the SFR during interactions are listed, with relevant observational tests. Current data suggest that several physical processes may contribute to star formation during interactions.

1. Introduction

It is by now part of the lore of galaxy research that galaxy interactions can, among other interesting effects, trigger bursts of star formation. This makes such systems useful laboratories for examining star formation in unusual environments, probing the behavior of a disturbed interstellar medium, and perhaps seeing processes that were important during galaxy formation. This paper reviews the evidence for the presence and scope of enhanced star formation during interactions, and presents several mechanisms that have been proposed to account for this excess.

Since we do not have "before and after" views of interacting galaxies, we are driven to perform statistical comparisons of large samples of interacting and non-interacting (sometimes called for brevity "isolated") galaxies. This offers the hope that we might measure shifts in the (already broad) distributions of properties tracing the SFR. Selection of both interacting and comparison samples can involve some subtlety, since the SFR we wish to measure is itself a function of galaxy type and luminosity. Furthermore, selecting program galaxies for obvious morphological signs of interaction biases the sample in favor of certain kinds of interactions seen at certain stages. Conclusions from such samples may not be generalizable to the whole population of encounters. Ideally, then, we should obtain comparable observations of samples of galaxies with the same distribution of Hubble type, luminosity (as measured before any alteration by the interactions), and environment (except, of course, for the presence of companions). Since interactions induce star formation and can therefore change the luminosity of a galaxy, and tidal disturbances can change the morphology, this sort of comparison cannot be attained in practice. However, the more closely matched the properties of interacting and control sam-

F. Combes and F. Casoli (eds.), Dynamics of Galaxies and Their Molecular Cloud Distributions, 243–250.

ples are, the greater the confidence one may have that any differences between the two are in fact associated with the interactions. Exactly how they are associated depends to some extent on the population of systems now seen undergoing interactions: galaxies that are only now undergoing their first mutual close approach should be more like isolated systems than those that have been in fairly close, slowly decaying circular orbits for most of the Hubble time (as discussed by Karachentsev 1988). Thus, dynamical understanding of the entire population of binary galaxies will be important in unravelling just how interactions influence galaxy evolution.

Only for extreme "starburst" systems (loosely defined herein as those in which the SFR exceeds 4-5 times its preburst level) can we be sure that most of the star formation that we observe has been triggered by a companion, simply because only a tiny fraction of "isolated" galaxies show such a high SFR. Some of the highest values are found for apparently merging systems; more detailed interpretation of their role awaits identification of a statistically representative sample of merger candidates without recourse to quantities strongly affected by star formation (such as far-infrared luminosity). Observations of these systems can sidestep the statistical approach, since the star formation in these cases must be due predominantly to the interaction. In some cases, the SFR in these systems is so high that a global wind can be set up, thus sweeping the galaxy nearly free of gas and leaving a system that may eventually resemble an elliptical (Graham *et al.* 1984).

2. Star-Formation Indicators

There are several of these for which sufficient survey material is available for statistical comparison. Further indicators (for example, in the X-ray band) should become available in the future. Note also that the discussion here is confined to luminous, gas-rich systems, which is to say spiral galaxies.

Optical colors. These reflect primarily stellar populations of age $\approx 10^9$ years or less, as well as being sensitive to the strength of such populations relative to any underlying older (bulge) population. Galaxies in pairs display a correlation of color indices (the Holmberg effect) tighter than that expected from the known correlation of morphological type (Holmberg 1958, Demin *et al.* 1984, Madore 1986). This provides evidence of similarly recent episodes of star formation. The distributions of color indices themselves were examined by Larson and Tinsley (1978) for systems in the Arp and Hubble atlases, showing that the strongly interacting systems in the Arp atlas show a large dispersion in colors that could be accounted for by bursts of star formation superimposed on a normal (older) component.

Finally, samples, such as the Markarian galaxies, selected for their strong near-ultraviolet continua (that is, blue color), are rich in paired and interacting galaxies (Heidmann and Kalloghlian 1974, Casini and Heidmann 1975, Kazarian and Kazarian 1988). These extreme systems probe the tail of the SFR distribution in much the same way as far-infrared flux-limited samples.

Direct counts of stars and clusters. The only work yet possible here has been on H II regions (or superassociations) and on supernovae. Statistics of supernovae show excesses of type II outbursts (and hence of young, massive progenitors) in interacting galaxies (Smirnov and Tsvetkov 1981, Kochhar 1990). Some interacting systems have extraordinarily luminous individual H II complexes (Petrosian, Saakian, and Khachikian 1985), while others have a normal H II region luminosity function even if the number of H II regions is unusually high (Keel and Laurikainen

1990). There are indications that the spatial distribution of H II regions is more centrally concentrated in interacting systems than in normal spirals (Bushouse 1987, Kennicutt *et al.* 1987).

Nuclear and integrated emission-line properties. Recombination lines trace the number of stars producing significant ionizing radiation (OB stars), with some sensitivity to reddening, obscuration, and mass function. For both nuclei and disks, several spectroscopic and imaging surveys have shown clear (statistical) excesses of emission in interacting systems (Keel *et al.* 1985, Bushouse 1987, Kennicutt *et al.* 1987), with some tendency for the excess to be stronger for more disturbed systems. This is found in Hα luminosity, in equivalent width (normalized to optical luminosity), and in Hα surface brightness (normalized to disk area). Further, the Hα equivalent width can be combined with continuum color indices to form a 2-color diagram with a very long effective wavelength baseline, and this may be interpreted much as done by Larson and Tinsley (Kennicutt *et al.* 1987).

Detailed comparison of multiwavelength images shows that, for galactic nuclei, the role of obscuration is strong and complex; ionizing clusters can contribute to Hα emission while remaining completely unseen in the optical continuum. Thus, differential comparisons are likely to be more reliable than absolute measures. In particular, model comparisons yielding burst ages or IMF slopes must be regarded as highly suspect. Also, there are systems in which emission lines may be influenced by such processes as shock heating (Keel 1990) or weak nuclear activity (Kennicutt, Keel, and Blaha 1989), so spectroscopic diagnostics are needed to be sure the luminosities we measure really reflect the SFR. For very dusty systems, it may not be clear how much the optical spectrum reflects the dominant energetics of the galaxy (compare the conclusions of Sanders *et al.* 1988 and Leech *et al.* 1989 as regards the role of star formation in the most luminous IRAS galaxies).

Thermal infrared. Two ranges have been studied - the 10μ window (offering excellent spatial resolution and modest sensitivity, probing high dust temperatures) and the far-infrared IRAS bands (excellent sensitivity but poor resolution, wider temperature range). Both are sensitive to a wider range of stellar masses than are H recombination lines. At 10μ, Cutri and McAlary (1985) found that galaxies from the Karachentsev (1972, 1988) catalog of paired galaxies have systematically higher 10μ luminosities (and detection probabilities) than isolated systems, which they interpreted as reflecting dust heated by increased numbers of young stars. Similarly, Lonsdale, Persson, and Mathhews (1984) found enhanced 10-20μ emission in galaxies selected for tidal distortions from the Arp Atlas.

There has been an enormous amount of work on the connection between IRAS emission and interactions (Soifer *et al.* 1984, Lonsdale, Persson, and Matthews 1984, Telesco, Wolstencroft, and Done 1988, Lawrence *et al.* 1989), but the results for an infrared-selected sample can be somewhat misleading if taken out of context. The far-IR properties of optically-selected samples (Bushouse 1987, Kennicutt *et al.* 1987, Haynes and Herter 1988, Sulentic 1989) show distributions much like those seen in Hα, with most systems modestly enhanced and a small percentage dramatically affected. It is this small tail of the SFR distribution that is strongly represented in FIR flux-limited samples, even though only a tiny fraction of all interacting systems are seen during such extreme bursts. These systems include many of the famous "superluminous" IRAS galaxies (Sanders *et al.* 1988). Statistical treatment of the IRAS data is limited by the poor resolution (generally requiring that pair members be treated together). In some very distorted galaxies, interpretation of the far-IR emission can be complicated by the possibility of more effective conversion of visible-wavelength radiation from an old stellar population into thermal infrared emission, when the dust is no longer confined to a single plane (e.g. Thronson *et al.* 1990).

Radio continuum emission. Spirals with high-surface-brightness radio disks are actively star-forming, and a large fraction are in interacting systems (Condon *et al.* 1982). The spectral index and surface brightness of the emission indicate a nonthermal origin, perhaps in supernova-accelerated particles radiating in fields along spiral arms. In some cases, the radio structure shows direct links to star-forming regions, and in some nearby objects, individual sources identified as supernova remnants can be found (Kronberg, Biermann and Schwab 1985; Noreau and Kronberg 1987). At least at the highest values, the surface brightness at centimeter wavelengths appears to reflect the supernova rate, and thus SFR in the relevant mass range. Over the 6-20 cm range, both disks (Hummel 1981) and nuclei (Hummel *et al.* 1987) show statistical enhancements in interacting systems.

3. Physical processes

All of these SFR indicators tell similar stories: the majority of interacting spirals have increases in SFR of order 30%, detectable only statistically, while a few experience increases of an order of magnitude. Such a wide range of responses may indicate sensitivity to internal dynamics, or to details of spin and orbit directions for particular encounters. There has been no shortage of proposed mechanisms to produce these effects. A non-exhaustive list includes:

Cloud collisions in a perturbed disk. If gas clouds in a disk have orbits that pass close to one another, a relatively minor perturbation to the potential could cause collisions that would not otherwise take place. Under the widespread assumption that cloud collisions are promising sites for star formation, this could lead to a very sensitive dependence of SFR on perturbations (Lin, Pringle, and Rees 1988). Struck-Marcell and Scalo (1987) find that the rate of collisions depends most sensitively on the ratio of timescales between the lifetime of a cloud and the mean collision interval, and that the SFR should undergo large excursions above and below the mean.

Collisions between clouds originally belonging to different galaxies. Similarly, during interpenatrating encounters or mergers, clouds might collide as a result of physical overlap of two disks. There is not necessarily any angular momentum barrier here, so a wide radial range of locations could be affected. Collision velocities could become quite high, in which case shock ionization or dissociation of molecular material would be important. Models by Olson and Kwan (1990) suggest that some fraction of high-velocity cloud collisions must be capable of yielding efficient star formation, to avoid complete disruption of molecular material without forming stars.

Tidally induced bars and radial gas motions. If a tidally disturbed system has a large enough region with a solid-body-like rotation curve, the companion can induce a bar that last much longer than the encounter itself. Noguchi (1988) has shown that this can lead to substantial channelling of gas into the nuclear region, perhaps leading to a nuclear starburst. In this case, interaction-induced star formation might outlive obvious morphological evidence of an encounter, except for the presence of the bar.

Tidally induced density waves. Tidal perturbations can produce very pronounced spiral density waves, as in the well-studied case of M51 (Toomre and Toomre 1972, Howard and Byrd 1990). These potential minima provide favorable sites for accumulation of interstellar matter and star formation, with the enhancement being in the fraction of the disk occupied by strong density peaks rather than any new process for triggering star formation.

Disk instabilities produced by perturbations in the potential. There is a remarkable agreement between regions of spirals in which star formation is observed, and regions in which gas is unstable by the Toomre (1964) and Quirk (1972) dynamical criterion (Zasov and Simakov 1988, Kennicutt 1989). A companion could distort the rotation curve (and local epicyclic frequency) by enough to render additional gas in the outer disk susceptable to collapse (perhaps via a phase change into molecular material). This seems to have been first suggested by E. Laurikainen. Unresolved issues include whether the interaction and collapse timescale are compatible, and the spatial distribution of resulting star formation.

Dumping of gas into E/S0 systems. Otherwise gas-poor galaxies could acquire significant material for star formation if physical transfer of gas takes place during an encounter with a gas-rich system. Sotnikova (1988) found that the proper conditions for gas transfer may exist in a significant fraction of close encounters between appropriate galaxy types, but it is unclear from emission-line statistics how often this might take place.

Direct impact of gas-rich dwarf satellites into disks This is a large-scale variant of the picture of cloud collisions between two galaxies. In this case, the obvious interaction with a bright companion is not the one causing the fireworks. Statistics of faint companions are not yet well enough determined to tell how important this process might be.

From general considerations, some of the induced star formation must be triggered by processes not requiring direct contact of disk material from different galaxies; some objects with high SFR are too far apart, and relatively undisturbed, so that internal effects of tidal stress must be responsible. Detailed modelling is thwarted by the great range of relevant physical scales in some of these cases. In testing these proposals, studies of the ISM in interacting systems, and understanding their dynamics, are crucial. For example, H_2 masses in combination with SFR estimates can suggest whether the SFR goes up because of creation or accumulation of new molecular gas (and normal accompanying star formation), or via an enhancement of the "efficiency" of star formation. A survey of 13 merger candidates by Young *et al.* (1986) suggested that the SFR reflects large molecular gas content; more recent results (Young, this conference) extend this by suggesting that the H_2/H I mass ratio is systematically larger in interacting systems than in normal spirals. CO surveys of complete and well-understood sets of both interacting and non-interacting galaxies are urgently needed (and in progress).

The responses expected for different kinds of system dynamics are distinct for various of these processes. Organized spiral density waves are triggered efficiently by prograde (direct) encounters, while retrograde encounters serve to heat the disk radially without such a coherent response. In both senses of motion, perturbations of the potential can lead to comparable distortion of individual orbits, so the rate of induced cloud collisions (for example) may not show a difference, but the collision *locations* will be quite different.

I have recently carried out a test for a difference between these two kinds of encounter, using systems from the Karachentsev catalog which could be identified from geometric and radial-velocity data as experiencing planar encounters seen edge-on. For such systems, a straightforward measurement of the rotation curves indicates which side of a galaxy is moving in the same sense as the companion, and thus which kind of encounter the galaxy is experiencing. Of 30 systems so far observed, nearly equal numbers are direct and retrograde. Both kinds show a large range (a factor 50) in SFR as judged from Hα; in particular, starbursts (Hα equivalent width 50-100 Å) occur in both direct and retrograde encounters. A difference is seen for both nuclei and disks in the sense that direct encounters produce more star formation (significant from this small sample at the 90% level). There then seem to be roles for some processes that are and some that are not sensitive to encounter direction. Perhaps not surprisingly, there seem to be several ways of inducing star formation by perturbing a disk.

The situation in merging galaxies may reflect yet additional processes; characteristic cloud-collision speeds will be of the same order as orbital velocities, so much more violent (and possibly disruptive) collisions are expected. Star formation in such an environment might well have different characteristic scales or initial-mass functions than seen in the familiar environment of a relatively quiescent disk.

4. Conclusions

It is relatively well established that galaxy interactions and mergers can increase the rate of star formation of spiral galaxies. It has proven difficult to specify how this increase is produced, for both observational and theoretical reasons. Major observational difficulties are the large scatter in SFR among interacting systems, so that we must seek statistical evidence of differences from the "normal" population of spirals, and the need for a more detailed census of the interstellar material in these systems. On the theoretical side, the role of cloud collisions is likely to be crucial, but most existing models treat the results of such collisions in a plausible rather than physically realistic manner. Dynamical modelling of a significant sample of systems may lead to some clarification, since various mechanisms for increasing SFR have different dependences on such parameters as relative spin and orbit direction and time from closest approach.

The new observations described in section 3 were obtained as a visiting astronomer at Lowell Observatory and at Kitt Peak National Observatory, which is operated by AURA, Inc., under cooperative agreement with the National Science Foundation. This work was supported in part by EPSCoR grant RII-8610669.

REFERENCES

Bushouse, H.A. (1987), *Astrophys. J.* **320**, 49.
Casini, C., and Heidmann, J. (1975), *Astron. Astrophys.* **39**, 127.
Condon, J.J., Condon, M.A., Gisler, G., and Puschell, J.J. (1982), *Astrophys. J.* **252**, 102.
Cutri, R.M., and McAlary, C.W. (1985), *Astrophys. J.* **296**, 90.
Demin, V.V., Zasov, A.V., Dibai, E.A., and Tomov, A.N. 1984, *Astron. Zh.* **61**, 625.
Graham, J.R., Wright, G.S., Meikle, W.P.S., Joseph, R.D., and Bode, M.F. (1984), *Nature* **310**, 213.

Haynes, M. P., and Herter, T. (1988), *Astron. J.* **96**, 504.

Heidmann, J., and Kalloghlian, A.T. (1973), *Astrofizika* **9**, 71.

Holmberg, E. (1958), Medd. Lunds Astron. Obs. Ser. 2, No. 136.

Howard, S.A., and Byrd, G.G. (1990), *Astron. J.* **99**, 1798.

Hummel E. (1981), *Astron. Astrophys.* **96**, 111.

Hummel, E., van der Hulst, J.M., Keel, W.C., and Kennicutt, R.C., Jr., (1987), *Astron. Astrophys. Suppl.* **70**, 517.

Karachentsev, I.D. (1972), *Soobsch. Spets. Astrof. Obs.* **7**, 1.

Karachentsev, I.D. (1988), *Dvoinye Galaktiki*, (Moscow: Nauka).

Kazarian, M.A., and Kazarian, E.S. (1988), *Astrofizika* **28**, 487.

Keel, W.C. (1990), *Astron. J.*, **100**, in press.

Keel, W.C., Kennicutt, R.C., Jr., van der Hulst, J.M., and Hummel, E. (1985), *Astron. J.* **90**, 708.

Keel, W.C., and Laurikainen, E. (1990), in preparation.

Kennicutt, R.C., Jr. (1989), *Astrophys. J.* **344**, 685.

Kennicutt, R.C., Jr. (1990), in *Paired and Interacting Galaxies*, J. Sulentic, W. Keel, and C. Telesco (eds.), NASA (in press), 269.

Kennicutt, R.C., Jr., Keel, W.C., van der Hulst, J.M., Hummel, E., and Roettiger, K.A. (1987), *Astron. J.* **93**, 1011.

Kennicutt, R.C., Jr., Keel, W.C., and Blaha, C.A. (1989), *Astron. J.* **97**, 1022.

Kochhar, R.K. (1990), in *Paired and Interacting Galaxies*, J. Sulentic, W. Keel, and C. Telesco (eds.), NASA (in press), 315.

Kronberg, P.P., Biermann, P., and Schwab, F.R. (1985), *Astrophys. J.* **291**, 693.

Larson, R.B., and Tinsley, B.M. (1978), *Astrophys. J.* **219**, 46.

Lawrence, A., Rowan-Robinson, M., Leech, K., Jones, D.H.P., and Wall, J.V. (1989), *Mon. Not. R. Astron. Soc.* **240**, 329.

Leech, K., Penston, M.V., Terlevich, R., Lawrence, A., Rowan-Robinson, M., and Crawford, J. (1989), *Mon. Not. R. Astron. Soc.* **240**, 349.

Lin, D.N.C., Pringle, J.E., and Rees, M.J. (1988), *Astrophys. J.* **328**, 103.

Lonsdale, C.J., Persson, S.E., and Matthews, K. (1984), *Astrophys. J.* **287**, 1009.

Madore, B.F. (1984), in *Spectral Evolution of Galaxies*, C. Chiosi and A. Renzini (eds.), (Dordrecht: Reidel), 97.

Noguchi, M. (1988), *Astron. Astrophys.* **203**, 259.

Noreau, L., and Kronberg, P.P. (1987), *Astron. J.* **93**, 1045.

Olson, K.M., and Kwan, J. (1990), *Astrophys. J.* **349**, 480.

Petrosian, A.R., Saakian, K.A., and Khachikian, E. Ye. (1985), *Astrofizika* **21**, 57.

Quirk, W.J. (1972), *Astrophys. J. Lett.* **176**, L9.

Sanders, D.B., Soifer, B.T., Elias, J.H., Madore, B.F., Matthews, K., Neugebauer, G., and Scoville, N.Z. (1988), *Astrophys. J.* **325**, 74.

Smirnov, M.A., and Tsvetkov, D. Yu. (1981), *Pis'ma Astron. Zh.* **7**, 154.

Soifer, B.T. *et al.* (1984), *Astrophys. J. Lett.* **278**, L71.

Sotnikova, N. Ya. (1988), *Astrofizika* **28**, 495.

Struck-Marcell, C., and Scalo, J.M. (1987), *Astrophys. J. Suppl.* **64**, 39.

Sulentic, J.W. (1989), *Astron. J.* **98**, 2066.

Telesco, C.M., Wolstencroft, R.D., and Done, C. (1988), *Astrophys. J.* **329**, 174.

Thronson, H.A., Jr., Majewski, S., Descartes, L., and Hereld, M. (1990), *Astrophys. J.* (in press).

Toomre, A. (1964), *Astrophys. J.* **139**, 1217.

Toomre, A., and Toomre, J. (1972), *Astrophys. J.* **178**, 623.

Young, J.S., Kenney, J.D., Tacconi, L., Claussen, M.J., Huang, Y.-L., Tacconi-

Garman, L., Xie, S., and Schloerb, F.P. (1986), *Astrophys. J. (Lett.)* **311**, L17.
Zasov, A.V., and Simakov, S.G. (1988), *Astrofizika* **29**, 190.