Revista Mexicana de Astronomía y Astrofísica, **27**, 77-82 (1993)

GALAXY PAIRS, STAR FORMATION, AND NUCLEAR ACTIVITY: SEARCHING FOR THE LINK

William C. Keel[1]
Department of Physics and Astronomy, University of Alabama

RESUMEN

Se revisa la evidencia de la conexión entre interacciones de galaxias con la actividad nuclear y la formación estelar. Al comparar la cinemática de pares de espirales con sus propiedades de formación estelar se muestra lo siguiente: No existe diferencia en la formación estelar nuclear o de disco entre las galaxias que sufren encuentros directos y retrógrados. Se notan conexiones entre el tipo de la perturbación cinemática en el disco y el nivel de la formación estelar (nuclear y de disco), y la amplitud de la velocidad máxima de las perturbaciones. está de acuerdo con los modelos en los que las inestabilidades globales son provocadas por perturbaciones externas.

La mayoría de los núcleos Seyfert que han sido examinados muestran regiones grandes de rotación de cuerpo rígido. La inducción de NAG, en esta muestra, parece estar conectada con una inestabilidad global en el disco. Tal inestabilidad puede a su vez, provocar los otros mecanismos propuestos para el transporte de gas y la compresión, tales como colisiones entre nubes moleculares gigantes o compresión de nubes en respuesta a los cambios de presión en los alrededores del medio interestelar difuso.

ABSTRACT

Evidence for links between galaxy interactions and both nuclear activity and star formation is briefly reviewed. A set of new observations has been designed to test several classes of models that have been suggested for such connections. Comparing the kinematics of paired spirals with their star-forming properties shows the following: There is no difference in either nuclear or disk star formation between galaxies undergoing direct and retrograde encounters, and very little difference as a function of projected separation out to 100 kiloparsecs. Connections are seen between the type of kinematic disturbance seen in the disk and the level of star formation (nuclear and disk), and with the maximum velocity amplitude of disturbances when scaled to the circular velocity. These facts are in accord with models where global instabilities are triggered by external perturbations, but not schemes that invoke cloud collisions or H I - H_2 interactions without such driving instabilities.

For Seyfert nuclei, most of the ones surveyed show remarkably large regions of rigid-body rotation, at a median radius of 2.1 kpc and extending in the most extreme cases to beyond 10 kpc (independent of the presence of a strong optical bar). The triggering of AGN, in this sample, appears to be connected to a global instability in the disk. Such an instability may in turn drive the other proposed mechanisms for gas transport and compression, such as collisions between giant molecular clouds or cloud compression in response to pressure changes in the surrounding diffuse ISM.

Key words: **GALAXIES: INTERACTIONS – GALAXIES: SEYFERT — GALAXIES: STELLAR CONTENT**

[1] Visiting astronomer, Kitt Peak National Observatory, operated by AURA under contract with the NSF; at Lowell Observatory, Flagstaff, Arizona; and at the Special Astrophysical Observatory, USSR Academy of Sciences

1. INTRODUCTION

Several kinds of evidence suggest important roles for galaxy interactions and mergers in triggering nuclear activity, in enhancing star formation on both nuclear and disk scales, and driving the overall evolution of many galaxies. These include optical colors (Larson & Tinsley 1978), emission-line strengths (Keel et al. 1985, Bushouse 1987, Kennicutt et al. 1987), radio-continuum and far-infrared detection statistics (Soifer et al. 1984, Lonsdale, Persson, & Matthews 1984, Lawrence et al. 1989, Sulentic 1989), and counts of AGN in paired galaxies (Keel et al. 1985, Dahari 1985). A convincing picture emerges from these studies, in which tidal interactions can alter the dynamics of at least the gaseous component in disk galaxies, with a redistribution that may feed the nucleus or trigger star formation across much of the galaxy disk. The responses include luminous starbursts, and the more common and more modest excesses in star formation that can be found only by statistical comparisons. The role of mergers is less clear, since there are no obviously complete samples of mergers that are not already selected on the parameter that we would like to measure.

Theoretical understanding of these issues is still primitive, in part because of the formidable complexity of the processes and physical scales involved. There have been many proposed mechanisms for gas redistribution during interactions and mergers; a short list includes star formation triggered by collisions between molecular clouds either within a single disk or originating in different galaxies, global instabilities introduced by a disturbance in the potential shape, rapid growth of a stellar bar which then funnels gas inward, and interactions between different phases of the ISM, where the relatively small molecular clouds respond to a pressure excess in the more widespread H I component. Various processes have distinct implications for our picture of disk dynamics and for the role of interactions in different environments, so that a way of discriminating among these proposals would be most useful.

I report here a test of these mechanisms, through study of the kinematics of samples of paired galaxies with and without prominent Seyfert nuclei. This allows study of correlations, within these sets of paired galaxies, among star formation rate, incidence of nuclear activity, direction of the companion orbit, and type of kinematic disturbance seen in the disk. Since many of the models above make definite predictions as to what kinds of interactions and disturbances should be most efficient, these tests should at least rule out some of the forms of those models which have been presented.

It should be stressed in any discussion of interaction-induced activity that the effect is statistical only. Many galaxies support either starbursts or Seyfert nuclei with no evidence of either a companion or an aging merger. The greatest importance of triggering of AGN may be in telling us that most luminous galaxies have the potential to host nuclear activity when appropriately perturbed, and may already have done so in the past. The degree of evolution seen for luminous QSOs virtually guarantees this, if they indeed require luminous host galaxies.

2. GALAXY SAMPLES AND DATA

In designing this study, I concentrated on spiral galaxies. These are both rich in gas, so that star-formation effects can be addressed, and have dynamically cold components, so that the structure of the disk and its history can be studied from kinematics and morphology. Two sets of galaxies were observed. One, to address the issues of star formation, was taken from the Karachentsev (1972, 1987) catalog of isolated pairs. It was designed primarily to allow sorting of galaxies undergoing perturbations by companions in direct and retrograde orbits, using geometric and velocity criteria that should isolate pairs with one galaxy viewed within 30° of its plane and also viewing the companion orbit within a similar angle to its plane (see Fig. 1 of Keel 1991). This filtering yielded 75 galaxies among the Karachentsev pairs, of which 59 were observed.

A similar orbit sorting is impossible for Seyfert galaxies, since internal obscuration prevents us from recognizing most Seyferts within 30° of the disk plane (Keel 1980). The sample criteria were thus relaxed, to include as many objects listed as paired in the catalog by Lipovetskii, Neizvestnii, and Neizvestnaya (1987) with well-resolved disks as were observable, except for those nearly face-on for which the disk kinematics are open to a wider variety of interpretations. Some orbit sorting is possible using morphologies for these pairs, since direct and retrograde encounters produce distinct kinds of perturbations (e.g., Howard et al. 1993). The sample as observed includes 29 Seyferts; an additional 2 were observed but showed no extended line emission.

Velocity slices (rotation curves) were measured from long-slit spectra taken with the GoldCam spectrograph at the Kitt Peak 2.1-meter telescope, plus a few additional galaxies measured with the multifiber system on the 6-meter BTA telescope of the Special Astrophysical Observatory. Uniform imaging of all the sample galaxies was obtained using the 1.1-meter Hall telescope at Lowell Observatory, in the R band for the Karachentsev sample and the V band for the Seyfert sample; the Seyfert images are considerably deeper, to allow classification of any tidal structure. The rotation curves were measured line-by-line along the slit by fitting blended Gaussian profiles to the red emission lines of Hα, [N II], and [S II]. Statistical errors were determined using photon statistics, incorporating the fitted linewidth and intensity. Sample rotation curves are shown as Fig. 1. Here, the error bars are $\pm 2\sigma$ at each point; the curves at the bottom of each panel are intensity slices along the slit in the continuum and Hα.

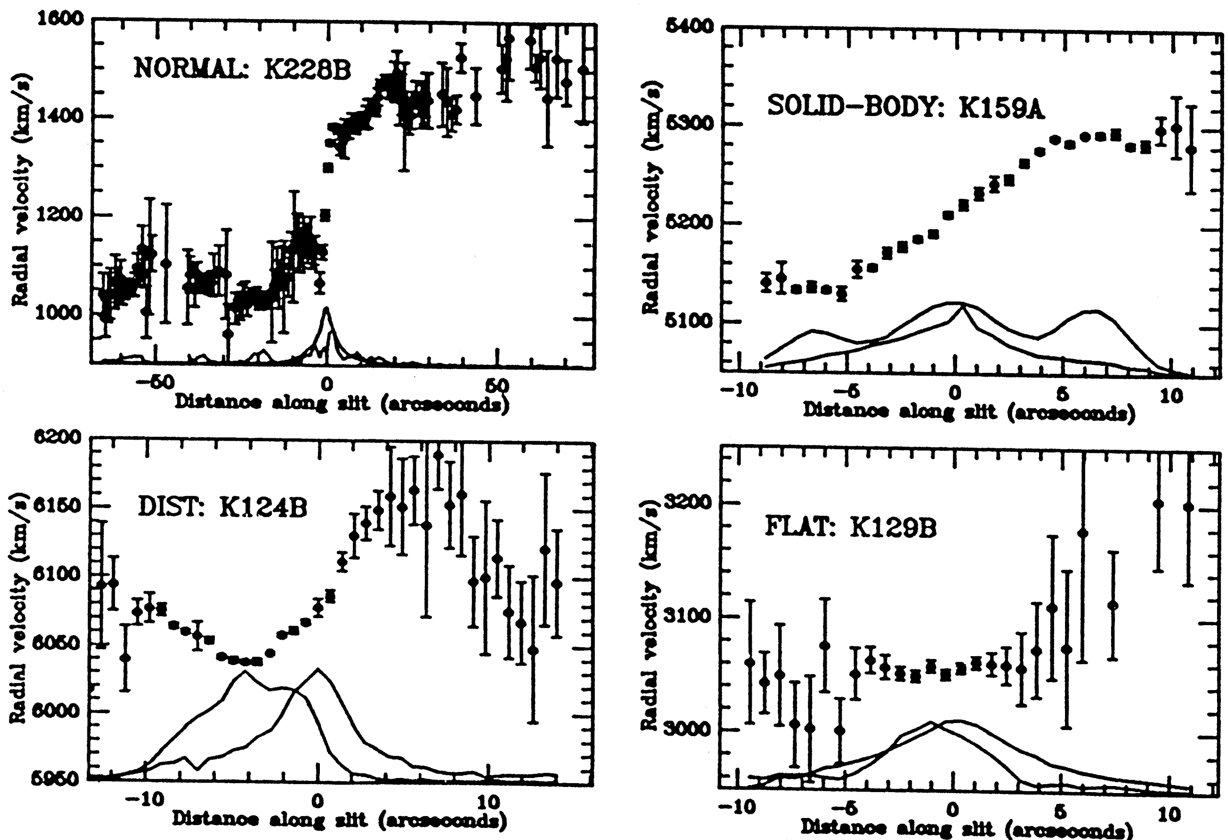

Fig. 1. — Sample rotation curves of various classes from the Karachentsev sample.

From the rotation curves, several types of kinematics could be found. Most fall into four broad categories, s labelled in Fig. 1 - a normal rotation curve (rising rapidly from the nucleus to a flat plateau), solid-body with a large area showing a linear radius-velocity relation), disturbed (with more general kinds of disturbance, sually on kiloparsec scales), and flat (with very small overall velocity ranges, tens of km s^{-1}, despite highly longated images). In addition, the amplitude of velocity disturbances and asymmetries could be measured. ndicators of star formation were taken (1) from Hα measures along the slit, incorporating radial gradients by ssuming that the piece of galaxy in the slit is representative, and in some cases (2) by decomposing IRAS n-scan data to separate the pair members.

3. STAR FORMATION AND KINEMATICS

3.1. Orbital Direction

Models that rely on cloud-cloud collisions by themselves predict a strong enhancement in collision-induced tar formation for direct encounters as opposed to retrograde ones (unless the disk gas physically collides). No uch effect is seen in the Karachentsev sample. In particular, nuclear and disk starbursts are equally common or direct and retrograde encounters. Since the enhancement in star formation persists to projected separations f 100 kpc, cloud collisions cannot be the whole story.

3.2. Rotation-Curve Class

There are significant differences in Hα equivalent width for the various rotation-curve classes. Relative star-formation rate increases in the order normal : solid-body : disturbed : flat rotation curves. The same order is found for nuclear and disk star formation, even given that the kinematic disturbances are found far from the center. Median values for the disk and nuclear Hα equivalent width are given in Table 1. Thus we might regard the kinematic signature seen at a given time during an interaction to be a symptom of the overall pattern, not the whole story.

Table 1 – Median Hα equivalent widths and rotation-curve form

Type	Nuclear EW (Å)	Integrated EW (Å)
Normal	3.5	7.3
Solid-body	24	17
Disturbed	26	30
Flat	89	79

The "flat" rotation curves, with the highest overall star-formation rate, are a special puzzle. They must either be tumbling, highly elongated systems seen face-on, or have undergone such a strong tidal impulse that the predominant motions are radial. In either case, the small amplitude of the velocity field will make it possible for gas clouds to grow well beyond the limits normally imposed by shear in galactic disks, to an extent limited rather by tidal forces. These may have a high probability of sustaining nuclear starbursts into the future, since the velocities observed are too low for rotational support without massive radial transport of the gas.

3.3. Velocity Amplitudes

There is no correlation between star-formation indicators and the velocity amplitude δv of any disturbance, when taking into account the projection factor due to our viewing direction. However, a broad correlation appears when this amplitude is normalized to the peak rotation velocity ΔV of the disk. This parameter enters into disk-stability criteria, suggesting that large-scale instabilities may be the forcing agent for star formation.

4. SEYFERT GALAXIES

The Seyfert sample includes a wide range of normal, disturbed, and solid-body rotators among galaxies with nuclei of both types 1 and 2. It is striking that large solid-body regions are common, with nearly 80% of the Seyferts showing a clearly resolved region of rigid rotation. Only 20-30% of non-paired galaxies (depending on Hubble type) show such features, as judged from the survey data of Mathewson, Ford, & Buchhorn (1992). These regions have a median radius of 2.1 kpc (for a Hubble constant of 75 km s^{-1} Mpc^{-1}), matching closely the value for the Karachentsev paired sample and larger than the typical values for more isolated spirals. This holds true for Seyfert galaxies of both types 1 and 2, which should be the case in the popular orientation scheme, which suggests that many of these nuclei would change classification if viewed from a different direction. Representative rotation curves for sample Seyfert galaxies are shown in Fig. 2.

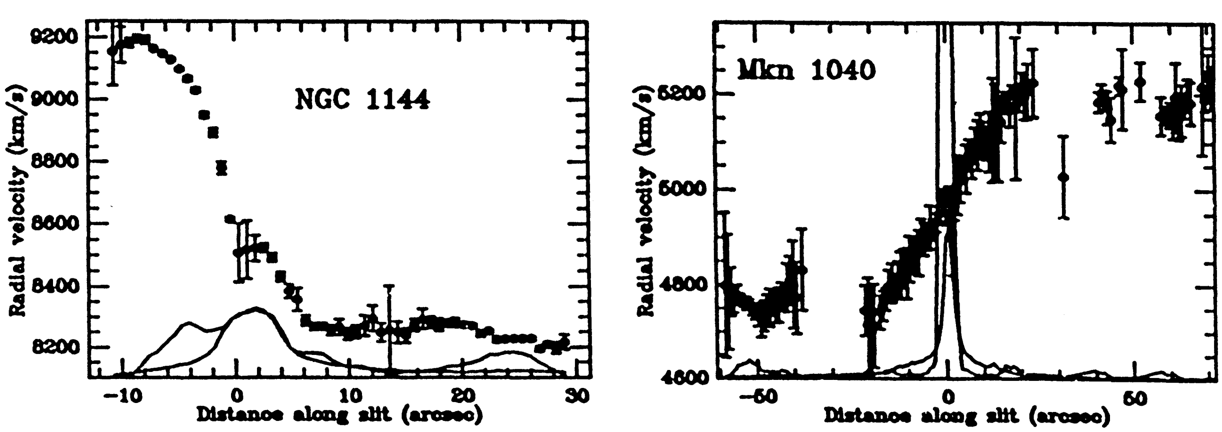

Fig. 2 – Rotation curves for paired Seyferts, showing large areas of solid-body rotation.

5. COMPARISON WITH MODEL PREDICTIONS

These data either present or reinforce several "facts" concerning galaxies' response to tidal perturbations:

For star formation, (1) the response is independent of the direction of the companion orbit relative to the isk. Direct and retrograde encounters are almost equally adept at producing bursts of star formation in nuclei r disks.

(2) Enhanced star formation is seen at a wide range of projected separations, out to 100 kpc, and the elative SFR has no strong dependence on this separation.

(3) The level of star formation is connected to both the type of kinematic disturbance seen in the disk, as een in the classification of rotation curves, and to its quantitative level when normalized to the disk circular elocity.

For nuclear activity, (4) all directions of companion orbit are well represented. This conclusion is based on ıatching to n-body simulations rather than direct velocity comparisons as for (1) above.

(5) Large regions of rigid-body rotation are found in most paired Seyferts, beyond both the frequency and ize of such regions in normal non-paired spirals.

These may be used to confront several classes of models for triggering both star formation and nuclear ctivity.

5.1. Cloud Collisions

Since much of the ISM in a typical disk, and in particular most of what directly drives star formation, esides in giant molecular clouds, collisions between such clouds are an obvious mode of redistributing the gas nd driving the SFR up. Collisions might both add an effective viscosity to the cloud population and enhance hock-induced star formation. Numerical experiments on the role of such collisions have been discussed by Olson : Kwan (1990), and by Mihos et al. (1991, 1992). Detailed models are hampered by the physical complexity f cloud physics, but based on plausible outcomes for various impact parameters and relative velocities, these tudies agree that the rate of SFR-inducing shocks should be dramatically higher in those collisions where either he companion is in a direct orbit, or the galaxies' cloud systems physically overlap at perigalacticon. Points (1) nd (2) above imply that cloud collisions, while probably a significant part of triggering, cannot *in themselves* ccount for the star formation in interacting galaxies.

5.2. Multiphase ISM Interaction

Jog & Solomon (1992) and Jog & Das (1993) have considered the effects of pressure changes in the more iffuse H I component on the star-forming molecular clouds, finding that shocks can be driven into the clouds ınd presumably triggering star formation) for a plausible range of conditions. These models require either that ıe H I distributions of the interacting galaxies overlap at perigalacticon, or that sufficient angular momentum distribution occurs to send clouds into the denser core ISM of a galaxy. The first of these seems ruled out y (2) above. The second scheme operates only when there is strong redistribution of molecular-cloud orbits, hich can occur only when some additional instability is present. Again, while these mechanisms are physically navoidable in the appropriate regimes, some additional process must operate.

5.3. Disk Instabilities

A classic result in continuum celestial dynamics is the existence of a stability threshold in a gravitating disk Toomre 1964). Physically, such an instability might be induced by a change in local density or the local velocity eld (for example, a change in the shear). This instability has been used by Lin, Pringle, & Rees (1988) to alculate expected radial mass transfer rates for typical encounters. They find that if the disk gas is marginally able, a small perturbation can lead to a large increase in radial transport due to nonaxisymmetric ("global") ıstabilities. On a smaller scale, Subramanian (1989) has discussed the stability of orbits in a perturbed core otential, with similar results: a small perturbation can change the topology of orbits and drive up the rate f orbit crossing (presumably driving cloud collisions). This scheme is less dependent on the details of the ncounter, as it serves to trigger a latent instability within the disk. Thus direct and retrograde encounters ıay be equally effective (especially near the nucleus, in which the rotation rate may render the distinction relevant).

These large-scale instabilities give the best match to the data on events in interacting galaxies, suggestin that this process may be the dominant driver for subsequent processes such as cloud collisions or radial ga motion. This is perhaps unexpected, since the original derivations were for single-component systems and w now understand the ISM to be a rich combination of several phases. However, this instability appears to play prominent role in controlling star formation in normal spirals, since the boundary where disk gas becomes stabl against these large-scale modes sets the cutoff for significant star formation (Zasov & Simakov 1988, Kennicut 1989). Processes in disturbed galaxies may be controlled by this same balance between disk self-gravity an shear disruption.

6. SUMMARY

I have presented spectroscopic and imaging observations of samples of star-forming and Seyfert galaxie designed to test several suggested physical agents for the observed connections between these phenomena an galaxy interactions. For both samples, the more fundamental process appears to be gravitational instability i the disk, as envisioned by Toomre (1964) and Lin, Pringle, & Rees (1988). Once such an instability has se in, subsidiary processes such as orbit crossing, cloud collisions, growth of a stellar bar, and perhaps interactio between various phases of the ISM may come into play. However, the behavior of star formation as a functio of encounter direction and separation does not allow these processes to be dominant without some triggerin instability.

For Seyfert nuclei, most of the AGN in pairs show large regions of rigid-body rotation, which is conduciv to similar instabilities with or without a stellar bar. Such kinematic signatures are also associated with elevate star formation in non-Seyfert paired galaxies, giving some hint that similar mechanisms can begin the radi flow of gas to feed the nucleus. Full details of these observations and the analysis are being submitted to th *Astronomical Journal.*

REFERENCES

Bushouse, H. 1987, ApJ, 320, 49
Dahari, O. 1985, ApJS, 57, 643
Howard, S.A., Keel, W.C., Byrd, G.G., & Burkey, J.M. 1993, ApJ (in press)
Jog, C. & Das, M. 1993, ApJ 400, 476
Jog, C. & Solomon, P.M. 1992, ApJ, 387, 152
Karachentsev, I. 1972, Catalog of Isolated Pairs of Galaxies, Soobsch. S.A.O., 7, 3
Karachentsev, I. 1987, *Dvoinye Galaktiki*, (Moscow: Nauka)
Keel, W.C. 1980, AJ, 85, 198
Keel, W.C. 1991, ApJL, 375, L7
Keel, W.C., Kennicutt, R.C., Jr., van der Hulst, J.M., & Hummel, E. 1985, AJ, 90, 708
Kennicutt, R.C., Jr. 1989, ApJ 344, 685
Kennicutt, R.C., Jr., Keel, W.C., van der Hulst, E., & Roettiger, K. 1987, AJ, 93, 1011
Larson, R.B. & Tinsley, B.M. 1978, ApJ, 219, 46
Lawrence, A., Rowan-Robinson, M., Leech, K., Jones, D.H.P., & Wall, J.V. 1989, MNRAS, 240, 329
Lin, D.N.C., Pringle, J.E., & Rees, M.J. 1988, ApJ, 328, 103
Lipovetskii, V.A., Neizvestnii, S.A., & Neizvestnaya, O.M., Soobsch. S.A.O. 55, 5
Lonsdale, C.J., Persson, S.E., & Matthews, K. 1984, ApJ, 287, 1009
Mathewson, D.S., Ford, V.L., & Buchhorn, M. 1992, ApJS, 81, 413
Mihos, J.C., Richstone, D.O., & Bothun, G.D. 1991, ApJ, 377, 72
Mihos, J.C., Richstone, D.O., & Bothun, G.D. 1992, ApJ, 400, 153
Olson, K.M. & Kwan, J. 1990, ApJ, 349, 480
Soifer, B.T. et al. 1984, ApJL, 278, L71
Subramanian, K. 1989, MNRAS, 238, 1345
Sulentic, J.W. 1989, AJ 98, 2066
Toomre, A. 1964, ApJ, 139, 1217
Zasov, A.V. & Simakov, S.G. 1988, Astrofizika, 29, 190

William C. Keel: University of Alabama, Dept. of Physics & Astronomy, P.O. Box 870324, Tuscaloosa, Al 35487-0324, U.S.A.