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PAIRED AND INTERACTING GALAXIES: CONFERENCE SUMMARY

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1. INTRODUCTION

This has been an excellent conference with a very international component and a rich and wide ranging diversity of views on the topical subject of paired and interacting galaxies. The southern hospitality shown to us by our hosts Jack Sulentic and Bill Keel has been most gracious and the general growth of the astronomy group at the University of Alabama is most impressive.

The conference began with the presentation of the basic data sets on pairs, groups, and interacting galaxies with the latter being further discussed with respect to both global properties and properties of the galactic nuclei. Then followed the theory, modelling and interpretation using analytic techniques, simulations and general modelling for spirals and ellipticals, starbursts and active galactic nuclei. Before the conference I had written down the three questions concerning pairs, groups and interacting galaxies that I hoped would be answered at the meeting: (1) How do they form? including the role of initial conditions, the importance of subclustering, the evolution of groups to compact groups, and the fate of compact groups; (2) How do they evolve? including issues such as relevant timescales, the role of halos and the problem of overmerging, the triggering and enhancement of star formation and activity in the galactic nuclei, and the relative importance of dwarf versus giant encounters; and (3) Are they important? including the frequency of pairs and interactions, whether merging and interactions are very important aspects of the life of a normal galaxy at formation, during its evolution, in forming bars, shells, rings, bulges etc., and in the formation and evolution of active galaxies. In what follows I shall summarize the meeting and where possible focus on these three central issues. Since this is a conference summary my references are all to papers presented at this meeting.

2. PAIRS AND GROUPS

Karachentsev presented his beautiful work on paired galaxies consisting of a homogeneous sample of these galaxies with a strict set of selection criteria. Of the 585 selected pairs, 98 were excluded on the grounds that their M/L values exceeded 100. The mean spatial separation of the final sample is 83 kpc and the velocity separation is 120 km s^{-1} . The M/L values ranged from 0-30. Pairs tend to have a similar Hubble type which seems to be due to formation processes and they also have similar colours. This effect was also found in the CfA redshift catalogue by Yamagata who coined the phrase twin galaxies for those with identical type and internal properties. Of course subtle consequences of the morphology density relation which would give similar effects need to be carefully taken into account here. Pairs are found in less dense regions of groups and clusters and 60% show evidence for tidal interactions and generally have an

by Yamagata who coined the phrase twin galaxies for those with identical type and internal properties. Of course subtle consequences of the morphology density relation which would give similar effects need to be carefully taken into account here. Pairs are found in less dense regions of groups and clusters and 60% show evidence for tidal interactions and generally have an enhancement of emission lines, radio power, infrared luminosity, and probability of being active. In general pairs are correlated with respect to their physical properties such as luminosity, size, type, M/L, and angular momentum, although there is no spin vector correlation. Pairs seem to follow the general hierarchical clustering law and dynamical estimates indicate that close pairs merge in 2-3 revolutions with a lifetime of approximately 1/5 of a Hubble time. Obvious questions that arise here are whether simple evolutionary tracks for single galaxies may be subtly different from evolutionary tracks of double galaxies? Do the paired ellipticals lie on exactly the same fundamental plane defined by the surface brightness-core radius-velocity dispersion relation as the unpaired ellipticals and do they evolve along the plane?

A detailed study of a differently selected sample presented by Charlton showed that the distributions of paired galaxies is flat with equal numbers per unit separation. If galaxy halos were the canonical size of 50-100 kpc, then one would expect there to be a drop in the number distribution at this separation scale. This is not the case and she conjectures that the resolution may lie in galaxies possessing very large halos. Large M/L values for groups themselves were cited by a number of authors including Quintana, who presented evidence from dynamical studies of groups around Dumbell galaxies that M/L values for these groups were of order 10^3 .

Hickson discussed his fundamental work on compact groups indicating that 30% of the galaxies appear interacting or disturbed, the morphological types are correlated, the morphology density relation was not strongly evident but there is a clear morphology-velocity dispersion relation. The overall luminosity function in compact groups is the same as that in the field although there is a deficit of faint galaxies and 1% of the light of the Universe is in compact groups. Sixty percent of the spiral galaxies studied in compact groups have peculiar rotation curves, 40% have compact nuclear continuum sources, the infrared luminosity is boosted by a factor of approximately two, and radio ellipticals are almost always first ranked. One question that arises is a consequence of the estimates discussed later that the merger timescale for these Hickson compact groups is 1/5 of a Hubble time. This implies that even with some fading that the post Hickson compact group phase should contain 3 – 5% of the total luminosity of the Universe. Is this significant component identifiable and what is it? Relatively isolated ellipticals and possibly cDs come to mind as possible relics.

The neutral hydrogen properties described by Williams indicate that for the smaller, more compact groups the HI distribution envelopes the group. For the larger groups the HI is still mainly in the galaxies (although they are HI deficient) and extended tail structure is clearly evident. A search for merger products in compact groups was described by Zepf who inferred that a frequency of 10 – 15% of the elliptical galaxies in compact groups should be blue and exhibit Balmer absorption lines as the signature of post merger products.

A lively panel discussion with substantial audience participation considered the question of an operational definition of tidal interactions and mergers. One possibility advocated by Simkin and Hutchings is that the mean separation should be $\leq 10R_{gal}$ but how big R_{gal} actually is including dark halo mass was not resolved within an order of magnitude. It was emphasized by Heckman that to really identify a merger product one should look at the old stars since much of the disturbed looking component could come from hydrodynamic effects such as outflows

and ionization effects from young stars. Even multiple looking cores could be a superposition effect. Burbidge strongly advocated that most if not all so-called mergers and interactions could be associated with outflows as opposed to inflows and infalls and considerable and lively discussion ensued. One argument given by the merger and interaction proponents was that they could model the data quite well and a detailed atlas of models including stellar and gaseous dynamics, stellar populations, ages etc. as discussed by Byrd seems a most useful tool for future observational analysis.

3. GALAXY INTERACTIONS

The global effects of interactions as discussed by Kennicutt are typically to enhance the $H\alpha$, the far infrared, and the radio power by factors of 1.5-2.0 over the values they would have, for a given type, for non-interacting systems. The evidence for enhanced star formation has been clear since the work of Larson and Tinsley but it was strongly emphasized that the tidal features contained 1/4 of the light of the system and that they are blue, consistent with the presence of massive stars in them. Concerning the question of supernovae rates in these systems it is not yet clear whether the observed rate is enhanced or not. The typical derived constraints for the burst times were 10-100Myr with star formation masses of order $10^8 - 10^{10} M_{\odot}$. Studies of the IMF are not yet complete with quite unresolved issues such as the deconvolution of the relative contribution of the disk, spheroid and nuclear components. Detailed spectral synthesis and modelling by both Lamb and Bernlohr gave limits to the burst age, and their best estimates of the lower mass cut off was ($\sim 4M_{\odot}$). Wolf-Rayet spectra both in the optical and infrared can be particularly useful here in establishing constraints on the behaviour of the upper mass region of the IMF.

As shown by Wright the optical images of the IR powerful galaxies are distorted by young stars and dust. However, the IR continuum images are smooth with a reasonably smooth $r^{1/4}$ law behaviour. As noted in a number of contributions physically meaningful separation of the red continuum component into the giant and supergiant populations is most important. In Arp 220 there are two tiny nuclei observed in the infrared with very high resolution that have also been identified in the radio using VLBI techniques by Norris.

The cosmological evolution of paired and interacting systems has been estimated by Koo and Zepf to increase as $(1+z)^4$ with an uncertainty in the exponent of about 2. Even with this uncertainty by a redshift of order 2-3 the merging and interaction level approaches 100%. This indicates that one might take the view that the merging and interactions that we see now are merely the tail end of the normal process of galaxy formation. Observations of galaxy morphology and interactions with the Hubble Space Telescope should settle this question.

Turning now to the study of the nuclear regions (as opposed to the global properties discussed by Kennicutt) of merging and interacting systems as discussed by Heckman, we note that for pairs the $H\alpha$, infrared and radio power increases by about a factor of 2 in the nucleus, and that for strongly interacting systems there is another factor of 2 enhancement. For a sample of FIR selected galaxies there appears to be a definite enhancement of interactions but there is no excess of close neighbours. For Seyferts there is some excess of close neighbours with about 15% of Seyferts showing strong interactions and 6% weak interactions as compared to typically 5% in the field. The effect seems much stronger for Seyfert IIs than Seyfert Is. Radio galaxies are in regions where the local density is enhanced by a factor of 2-3 and bridges and tails are clearly evident for the most powerful radio galaxies. For QSOs with observed fuzz, 30 - 100% seem to

be interacting. In terms of importance of the interaction process to the activity in the central region it is only the starburst galaxies and possibly the powerful radio galaxies and QSOs that seem to have a reasonably strong correlation with the effect on Seyferts and radio quiet QSOs being significantly more subtle.

The panel discussion on the reality of the cosmological redshift hypothesis was energetic, enthusiastic, and stimulating with many ideas put forward to support a diverse set of views. The end result is a set of predictions that this reviewer solicited from the most vocal participants that may be useful as a priori tests.

Steve Schneider: Secondary peaks in the δV distribution will move to higher velocity for narrower predicted physical separation (for homogeneously selected galaxy pairs). This will be a weak effect if the cutoff radii are within the halo radius.

William Tift: We have been asked to make some predictions which might serve as benchmarks for future evaluations of redshift quantization. I will interpret this slightly more broadly to concern the nature of the redshift in general.

1) I will predict that continued work on close pairs of galaxies (product of redshift in km s^{-1} times separation in degrees < 300) will verify the exclusion of $\Delta V = 0$, and searches at larger separation will not find any excess, lost due to selection, which will fill in the hole. Normal dynamics and simple projection predicts a peak at zero.

2) I think the verification of the minimum between the 72 km s^{-1} peak and the 145 km s^{-1} peak for differential redshifts in close isolated pairs constitutes a second good bet. Perhaps this can be more simply put as the *multiple* nature of the peaks and valleys will continue to be verified.

3) Already mentioned in my introductory statement, and reinforced here, I believe that variability in redshift will be quite convincingly demonstrated within the next 5 to 7 years if not sooner.

Paul Hickson: About 35% of all my compact groups will be found to contain exactly one discordant redshift, as expected by chance superposition. These galaxies will generally be smaller and fainter than other group members, but not always as small or faint as typical galaxies at their redshift. They will be found near the centre of the group more often than expected. It will be possible to explain these effects by gravitational lensing from smoothly distributed dark matter in the groups.

Jack Sulentic: Dense group predictions:

(1) The majority of dense groups ($\sim 80\%$) will turn out to be physically dense systems rather than chance alignments of some kind. This realization will lead to a fundamental change in the dynamical theory of galaxy groups. This will involve something that inhibits merging in a few crossing times (or something related to 2).

(2) The discordant redshift groups will turn out to be:

(a) optical configurations (10 groups) and a lot of,

(b) lensed configurations *or* something new (young systems; $t \leq 10^9 \text{ yr}$).

Geoffrey Burbidge: It will slowly be accepted that some significant part of the redshifts of extragalactic objects are not associated with the expansion of the universe. This will lead to a revolution in this field. Eventually on or two leaders will change their minds and then the bandwagon will change course. (In the interim the dirty tricks will continue. Papers will be interminably refereed, observing time on the Hubble Telescope and elsewhere will be denied, grant applications will be turned down, and "safe" people only will give summary talks.)

I hope that this happens in time for the radicals (those in Alabama plus Chip Arp and Fred Hoyle) to be acknowledged. However the odds are not good. Two previous cases come to mind. Wegener (continental drift) died before his ideas were accepted, as did Zwicky, who was hated by many at Caltech as Arp is, or at least as are his ideas today.

DYNAMICAL THEORY OF PAIRS AND INTERACTIONS

Significant progress has been made in the modelling of the dynamics of pairs and interactions. This work was elegantly summarised by Athanassoula. She noted that for one of the best merger cases, namely the Antennae, Barnes and Hernquist can now model the thin tails and the close separation of the cores. Some uncertainty remains about the relative velocity and the initial orbit eccentricity.

Spiral structure can be driven by prograde companions and a one-armed leading spiral is possible for retrograde companions if the main spiral galaxy has a low halo to disk ratio. She showed that the Q-parameter is not important for controlling the amplitude of the driven spiral due to non-linear disk heating effects and also that increased forcing does not imply a better spiral pattern. Clearly bars are enhanced by companions since the frequency of SAB, and SBB is 63% in the field and 80% in binary galaxies. An initially unbarred galaxy will have the bar instability growth significantly enhanced by a companion. If the galaxy is already barred the bar will be strongly increased in strength and will then decrease after the encounter. For out of the plane encounters they will have a shorter time to act and disk thickening may occur.

The dynamics of E-E pairs have asymmetric light distributions, U-shaped profiles and rising velocity dispersion profiles as discussed by Kirk Borne. His simulations show the stubby tails and indicate interesting orbits. Detailed simulations of large samples are necessary to determine the frequency and significance of interactions in these and other systems. Using the impulsive approximation, Chatterjee proved that without halos the merging frequency would be two orders below the present observed value of 1%. He concluded that halos are needed and indicated that with massive halos the correct value is achievable.

Double and multiple nuclei were discussed by Khachikian who reminded us of some of the theories of their origin including mass creation, double vortices and splitting of nuclei to give the twin nuclei that have nearly identical properties. Bulge formation from mergers was discussed by Roos using Monte Carlo simulations and the issue was raised about absence of evidence for counter rotating bulges. A beautiful dynamical friction calculation done analytically by Polyachenko was presented for both disks and halos which agreed exactly with the detailed numerical calculations.

Including both gas and stars in his numerical simulations, Noguchi gave a prescription for star formation due to cloud-cloud collisions and further prescribed the energy input fed back by supernovae into the interstellar medium. In models where a companion flies by a galaxy going bar unstable the bar instability is strongly enhanced, shocks form, significant stellar disk heating occurs and a large mass accumulates in the central regions. The duration of this phase is a few rotation periods. This set of calculations has real likeness to the observations of starbursts. Similar detailed calculations have been carried out by Hernquist.

The physics of compact groups can be modelled in two ways as discussed by Mamon. Self-consistent N-body codes such as the detailed group simulation of Barnes are extremely accurate and we have confidence in the results. The film resulting from their work shows how important are the three dimensional nature of the orbits. Many obvious two-dimensional mergers and

interactions in fact turn out to be quite distant flybys in three dimensions. The thin tidal tails were apparently reproduced and give a significant contribution to the light, the merging process was relatively long with the resulting merged system having low angular momentum and exhibiting shell structures. The tidal tails are then blue and appear to have a dynamical age of 50-150 Myr.

The more explicit Fokker-Planck style calculations of Mamon have an advantage in their speed of execution and their inclusion of much more physics that is however put in by hand. For M/L of ~ 40 , the merger timescale was found to be $\sim 3Gyr$ consistent with the more detailed dynamical calculations. With more dark matter in the halos the timescale is significantly altered and there was considerable debate whether it lengthened or shortened. If more mass is put in the halos, the merger cross section is increased but there is then less mass in the smooth background potentially decreasing the drag due to dynamical friction. More mass in a smooth background will increase the dynamical friction but the halos will be smaller. This important issue should be unambiguously resolvable in the near future. The question of the frequency of chance alignments within the compact groups was much debated here and ranged from 50% – $10^{-6}\%$, clearly a narrower range is preferable. what is needed here is a series of cosmological simulations with a high dynamic range where individual galaxies and halos can be resolved.

5. GENERAL THEORY

The general problem of fuelling active galactic nuclei utilizing interactions as outlined by Shlosman is how to get $10^8 M_{\odot}$ from the galactic regions of dimensions of order say kpc into a region of order the size of the solar system at the rate of $1M_{\odot}yr^{-1}$. It seems possible to do the job down to scales of say 100pc as shown in the simulations of Noguchi and Hernquist but from then on the problem is harder to crack both observationally, and theoretically, although here again the resolving power of the HST will prove most useful. The questions still remains how the extrinsic forcing due to interactions, mergers, and sinking satellites influences the central regions via non-axisymmetric disturbances such as bars, triaxiality, spiral waves, or direct deposition in sinking satellites or mergers with sufficiently dense cores. One clue from starbursts is that the self gravity of the gas may be important.

Most of the posters showed beautifully detailed multiwavelength observations of individual objects and also many impressive models with both gas and stars incorporated. Realistic models of the interstellar medium that can be included in the simulations are still somewhat off. All this work will still be rather uncertain until more is understood about the star formation process. The general impression is that large quantities of complete samples with many detailed multi-wavelength and complete modelling will unravel some of the problems we have come to at this meeting. Very significant progress was reported at this excellent meeting and the pace shows no signs of slowing, quite the contrary the mood here is to go away, work hard and solve the newly posed problems as soon as possible. Once again we thank the organizers, Jack Sulentic and Bill Keel for making this such an enjoyable and stimulating meeting.

It is a pleasure to thank Steve Zepf for a careful reading of the manuscript and Paul Hickson for enlightening correspondence on the evolution timescale for compact groups with evolving halos.