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(NASA-CR-194483) IRAS HIGH RESOLUTION STUDIES AND MODELING OF CLOSELY INTERACTING GALAXIES. GALAXY COLLISIONS: INFRARED OBSERVATIONS AND ANALYSIS OF NUMERICAL MODELS. UV SPECTROSCOPY OF MASSIVE YOUNG STELLAR POPULATIONS IN INTERACTING GALAXIES Final Technical Report, 15 Aug. 1989 - 14(Illinois Univ.) 10 p

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FINAL TECHNICAL REPORT

NASA Grant (NAG 5-1241)

entitled (variously)

IRAS High Resolution Studies and Modeling of Closely Interacting Galaxies
and
Galaxy collisions: Infrared Observations and Analysis of Numerical Models
and
UV Spectroscopy of MassiveYoung Stellar Populations in Interacting Galaxies

This grant covered both observational studies and theoretical modelling of interacting galaxies. As a consequence the report is divided into two parts, one on each aspect of the overall project.

I. Theoretical modelling

The numerical studies of colliding galaxies originated from a collaboration between Bruce Smith (NASA Ames), Richard Miller (University of Chicago), and Susan Lamb (University of Illinois), using numerical models produced by Miller and Smith at NASA Ames and elsewhere. Some results of this collaborative work are reported in papers reproduced below (see papers P1 and P2). More recently, Lamb has performed numerical experiments (in collaboration with Richard A. Gerber, a graduate student at the University of Illinois) using a combined n-body/SPH code written by Dinshaw Balsara (now of the Johns Hopkins University). This has been run at the National Center for Supercomputer Applications sited at the University of Illinois. Some results of this work have been described in the appended papers and abstracts (see A1, A2, and P3).

II. Observational Studies.

The observational studies included both IRAS studies, using the IPAC data base, and new IUE observations. These studies were done primarily in collaboration with Howard Bushouse (previously at Northwestern University, currently CSC Corporation).
A list of the papers resulting from this work follows.

IRAS Observations of an Optical Sample of Interacting Galaxies, S. A. Lamb, H. A. Bushouse, M. W. Werner, and B. F. Smith, (1988) in 'Comets to Cosmology: Third International IRAS Conference,' ed. A. Lawrence (Springer-Verlag: New York and Berlin), p. 257.

IRAS Observations of an Optically Selected Sample of Interacting Galaxies, H. A. Bushouse, S. A. Lamb, and M. W. Werner, (1988) Ap. J., 335, 74.

Star formation in infrared bright and infrared faint starburst interacting galaxies, S. A. Lamb, H. A. Bushouse, and J. W. Towns, (1989) Bull. Am. Astron. Soc. 21, 1163.

Star formation in infrared bright and infrared faint starburst interacting galaxies, S. A. Lamb, H. A. Bushouse, and J. W. Towns, (1990) 'Paired and Interacting Galaxies', IAU Colloquium 124, J. W. Sulentic, W. C. Keel, C. M. Telesco (Eds.), NASA Scientific and Technical Information Division, p. 303.

IUE Observations of Interacting Starburst Galaxies, S. A. Lamb, H. A. Bushouse, and J. W. Towns, (1990) Proc. of 'Evolution in Astrophysics: IUE astronomy in the era of new space missions', E. J. Rolfe (Ed.), ESA Publications Division, p. 591.

A1. Potential Sites for Star Formation in Interacting Galaxies: Numerical Experiments

[Abstract of a paper presented at the January 1990 Meeting of the American Astronomical society by R. A. Gerber, D. S. Balsara, and S. A. Lamb (Univ. of Ill.) Bull. Am. Astron. Soc. 21, 1163, 1989].

Collisions and close interactions between galaxies can lead to bursts of star formation, but sometimes little or no enhancement in star formation is observed even in those systems which originally contained a disk (Bushouse, 1984, P.A.S.P., **96**, 273; Keel, *et al.*, 1985, **90**, 708; Bushouse, 1986, A.J., **91**, 255). In those galaxies experiencing enhanced star formation the new stars are usually concentrated in the central region (radius ~ 2 kpc in a typical galaxy) but, occasionally a large disk shows enhancement or a concentrated region away from either nucleus is very visible in Ha studies (Bushouse, 1987, Ap.J., **320**, 49; Kennicutt, *et al.*, 1987, A.J., **93**, 1011). In this study we experiment with models of colliding disk galaxies to investigate the role of dynamical processes in producing potential sites for star formation. We have carried out fully self-consistent N-body experiments in which one galaxy is modeled by an active massive spherical halo and an exponential disk which contains one-third the mass of the halo, and the other model galaxy has a spherical component only. In these experiments we look at the role played by the orientation of the disk's angular momentum vector with respect to the direction of approach of the two galaxies in determining the locations of, and duration of high density regions. We look for flows of material toward the nuclei of the galaxies and the formation of 'isolated islands' of high density in regions away from either nucleus. We have chosen to model collisions of galaxies of equal mass and size so that our results are of relevance to the optical observational surveys of Bushouse and Keel, Kennicutt, *et al.* (Their samples are selected to contain interacting systems in which the galaxies of an interacting pair have comparable luminosities - to within a factor of a few). We also investigate the self-consistent response of the spherical halo during an encounter to see if this plays an important role in the development of high density regions, and compare the results with those of models using a rigid background halo potential.

A2. Combined Hydrodynamical and N-Body Studies of Colliding Galaxies: The Formation of Ring Galaxies

[Abstract of a paper presented at the January 1991 Meeting of the American Astronomical Society, by R.A. Gerber, S.A. Lamb (Univ. Illinois at Urbana-Champaign), D.S. Balsara (Johns Hopkins Univ.) Bull. Am. Astron. Soc. 22, 1943, 1990]

We present results of 3-dimensional, numerical studies of collisions between a disk galaxy and an extended elliptical galaxy which have been performed using a combined N-body/fluid dynamical code. The code allows both an N-body representation of the stars and a Smooth Particle Hydrodynamics (SPH) fluid dynamical representation of the gas component of galaxies. The experiments have been performed on the Cray 2 supercomputer at the National Center for Supercomputing Applications. We describe experiments which involve a head on collision between the two galaxies, with the impact taking place along the spin axis of the disk galaxy. We compare our results with both observations of ring galaxies and with previous N-body calculations and analytical results for these galaxies. In our models we locate the positions of shocks in the gas and compare the gas densities achieved with those expected for isothermal and adiabatic shocks. Gas behavior near the shock regions is explored and it is shown that motion in the vicinity of the ring has a complicated three-dimensional structure. The gaseous ring has a greater amplitude and is more spatially localized than the corresponding stellar ring. If new star formation is triggered in the shock regions, the stars formed by this process may produce sharper rings than those seen in purely N-body experiments.

A3.

[Abstract of a paper presented at the January 1992 Meeting of the American Astronomical Society, by R.A. Gerber, S.A. Lamb (Univ. Illinois at Urbana-Champaign), D.S. Balsara (Johns Hopkins Univ.) Bull. Am. Astron. Soc. xx, xxxx, 1991]

The galaxy Arp 147 belongs to a class of objects believed to have formed a ring as a result of a collision with a second galaxy. We have produced a combined stellar and gas dynamical computer model of a pair of interacting galaxies which exhibits many of the features seen in Arp 147. In our model the ring forms following the passage of a second galaxy approximately perpendicularly through the disk of Arp 147, about two radial scalelengths from the center of the disk.

Photometry of Arp 147 by Schultz etal (1990) reveals vigorous recent star formation has occurred primarily in two knots diametrically opposite each other. Photometry and IUE observations show a lack of recent high levels of star formation in the knot closest to the second galaxy, which lies midway between the active star formation sites (Schultz etal 1991). These observations are consistent with this knot, which is photometrically the brightest knot in the ring, being the remnant nucleus of Arp 147.

We present four different aspects of our computer model and relate them to the observations of Arp 147. These are (1) the stellar surface density as seen by integrating along the line of sight, (2) the gas surface density along the line of sight, (3) the three-dimensional gas space density and (4) the locations of strong shocks in the gas.

The stellar surface density is strongly peaked at the location of the remnant nucleus. The gas surface density has a peak at the same location, but also has enhancements around the ring on opposites sides, similar in position to the observed regions of active star formation in Arp 147. The three-dimensional space density of gas in the model is greatest in a region corresponding to one of the star-forming knots in the observed galaxy. A secondary maximum occurs diametrically opposite the first. The gas space density shows no enhancement near the old nucleus. Further, strong shocks occur in our model only in the regions of high gas space density, that is, away from the nucleus.

Our results are consistent with the interpretation of the brightest observed knot of Arp 147 as the remnant nucleus. This knot is made up of the older stars that existed before, the interaction. Further, our model is consistent with a picture in which star formation bursts occur in regions of enhanced gas space density and regions of strong shocks in the interstellar medium. Finally we note that if, indeed, the dynamical evolution of Arp 147 is similar to our model, our results suggest that relating the line of sight integrated gas surface density to a star formation rate (eg., using a Schmidt law) may lead to misleading conclusions in interacting systems such as these.

P1. Models of colliding galaxies: kinetic energy and density enhancements
R. A. Gerber, S. A. Lamb, R. H. Miller, and B. F. Smith,.
in Dynamics and Interactions of Galaxies, Wielen (Ed.), Springer - Verlag, p. 223, 1990.

1 Introduction

Collisions and close encounters between galaxies have a profound effect upon the galaxies involved. For example, morphological changes can be pronounced. A very obvious effect of interactions on galaxies is a mean increase in their far infrared luminosities as detected by IRAS (1). This observed excess in infrared luminosity has often been invoked as evidence of increased star formation in these systems (2).

Theoretical calculations show that a galaxy initially experiences a roughly homologous infall as a result of a close passage (3,4) with the stars gaining kinetic energy and increasing their space density (5). The interstellar medium will gain kinetic energy along with the stars during this infall stage, resulting in an increase in cloud collisions which may lead to enhanced rates of star formation.

Here we show the results of using N-body models to obtain information which will be useful in probing some aspects of the relationship between galaxy collisions and star formation. The models allow us to identify regions of increased density in the systems and to calculate the increase in kinetic energy which is available to trigger star formation. The calculations model the stellar component of galaxies, but it is anticipated that the gas will follow the stars during the initial infall stage that we are concerned with here.

2. The Models and Results

The experimental collisions we use are those described in (3,5). These are the results of fully self consistent N-body calculations in which the self-gravity of each galaxy is included. The models are produced using a particle-mesh technique and contain approximately 100,000 particles. The collisions have varying values of orbital angular momentum and two different values of initial orbital energy corresponding to a parabolic sequence, with orbital kinetic energy equal to potential energy, and a hyperbolic sequence; with a difference in initial orbital kinetic energy between the two series of about a factor of two. All encounters are interpenetrating, ranging from almost head on to almost grazing.

We analyze collision experiments of spherical galaxies, for both equal mass encounters and galaxies with a mass ratio of 2:1. We also investigate collisions between equal mass spherical galaxies with cold, thin, rotating disks embedded in them. In these the disks contribute only 1 percent of the total mass. Each spherical galaxy is the stellar dynamical analog of an n=3 polytrope and the disks have a surface density that falls off as R^{-1}. In the following discussion, we give time units in terms of a typical stellar crossing time in an unperturbed galaxy, t ,and distances in terms of the unperturbed galaxy half-mass radius.

A Equal mass galaxies.

The total kinetic energy and the density peak somewhat after close approach. For example, the rms velocity in a head on parabolic collision increases 42 percent over the starting value, reaching its maximum 0.12 *t* after close approach. The relative increase in the rms velocity decreases with increasing impact parameter, and very little effect is noticed for the encounter with our largest impact parameter (2.6 *l*.). We find that the parabolic collisions lead to larger peak rms velocity than do the hyperbolic encounters for a given separation at close approach, although the difference between the two series is only on the order of a few percent.

The galaxies reach their most contracted state up to 0.25*t* after close approach and, in the case of the almost head on parabolic collision, the central density of the galaxy's own particles has doubled by this time. Generally, when one takes into account the contributions of the particles of both galaxies the density can be as high as 2.5 times the initial value.

In the disk-halo experiments we find that face on collisions produce a larger increase in disk particle kinetic energy than those in which the disks hit edge on. We find that the disk particles pile up into spiral and strong linear features soon after closest approach and the disks contract, following the overall gravitational potential produced by the halo.

B Unequal mass galaxies.

The collision affects both galaxies in the unequal mass pairs, but it has a more profound effect on the less massive of the two. For example, the kinetic energy of the less massive one more than triples during the head on parabolic collision. There is a time lag between the kinetic energy peaks of the two galaxies, with the larger galaxy reacting more slowly and reaching its energy peak up to .25 *t* after the smaller galaxy, where t is defined as the stellar crossing time in the unperturbed larger galaxy. We find that the rms velocity of the larger galaxy increases more than that of the smaller galaxy. A major feature of the unequal mass experiments is the destruction of the smaller galaxy except at our larger impact parameters.

3 Implications for Star Formation

We expect that any gas present in real galaxies will follow the stars during the initial infall stage of the collision and this will lead to an increase in cloud-cloud and cloud-intercloud collisions. Interpenetration of the galaxies may also produce very high energy collisions in the interstellar material and together these effects may result in either disruption of the star forming regions or enhancement in the rate of star formation due to an increase in the number of star forming centers and possibly to an increase in the size or activity of these regions. Our calculations give us an approximation to the density and kinetic energy increases of interstellar material during the early infall stages and allow us to estimate timescales for possible increases in the star formation rate. We note that for a head-on, parabolic collision between equal mass spherical galaxies of mass 5×10^{10} solar masses and radius 16 kpc, the kinetic energy peaks 8 million years after minimum separation and the central density of the galaxies' own particles reaches its maximum another 8 million years later. Thus one might expect to observe a significant increase in the star formation rate about 10^7 years after the first passage of such galaxies. The timescale for merger of these galaxies (about 10^9 years) is not the relevant one for the initiation of star formation.

Our finding that the larger and smaller galaxies in an interacting system react dynamically on different time scales suggests that star formation may be initiated at different times in such a pair. For example, if the larger galaxy has a mass of 6.7×10^{10} solar masses and a radius of 16 kpc and the smaller galaxy has a mass of 3.4×10^{10} solar masses and a radius of 11 kpc, the larger may have a time lag of up to 16 million years in its kinetic energy peak. This may explain why some pairs of interacting disk galaxies, which are otherwise similar, exhibit very different current star formation characteristics (6).

Some interacting systems, such as UGC 12914/5, are observed to have large HII regions far away from either nucleus. These systems may be explained as the result of an interpenetrating collision of two disk galaxies in which a high density was obtained part way between the two nuclei. If the angular momentum and kinetic energy roughly cancel then a somewhat detached star forming region may result. We see evidence of this possibility in collisions with impact parameters around 0.9 to 1.3 l. (from 4 kpc to 6 kpc for a galaxy of 6.7×10^{10} solar masses).

Interacting counter rotating disks may help reduce the total angular momentum of the gas in interacting systems and thus allow the gas to spiral in towards the nuclei and accumulate there. Strong density enhancements are found in the disk particles during collision, and these are often in the form of strong, if temporary, linear (bar-like) features. The existence of such features in real systems appears correlated with high rates of star formation .

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P2. Potential sites for star formation in interacting galaxies
R. A. Gerber, S. A. Lamb, R. H. Miller, and B. F. Smith,
in Windows on Galaxies, Fabbiano, G., Gallagher, J. and Renzini, A. (Eds.), Kluwer Academic, p. 366, 1990.

Interacting galaxies have a mean increase in their far infrared luminosities as detected by IRAS (1), and this observed excess in infrared luminosity has often been invoked as evidence of increased star formation (2).We have used the N-body models described in (3,5) to obtain information which is useful in probing some aspects of the relationship between galaxy collisions and star formation. The models are the result of fully self consistent calculations of spherical galaxies in which the self-gravity of each galaxy is included. The collisions are deeply interpenetrating with the galaxies initially either on parabolic or mildly hyperbolic orbits.The encounters are of equal mass galaxies or galaxies with a mass ratio of 2:1 and some include cold, thin, rotating disks.

Theoretical calculations show that the stellar component of a galaxy initially experiences a roughly homologous infall as a result of a close passage (3,4,5) and the interstellar medium will gain kinetic energy along with the stars during this infall stage, resulting in an increase in cloud collisions which may lead to enhanced rates of star formation. The experiments model the stellar components of galaxies, but it is anticipated that the gas will follow the stars during the initial infall stage when the largest burst of star formation is likely to occur. We identify regions of increased density in the systems and obtain an approximation to the density and kinetic energy increases of interstellar material during the first infall stage and estimate timescales for possible increases in the star formation rate. We note that for a head-on, parabolic collision between galaxies each of mass 5×10^{10} $M_{\odot}$ and radius 16 kpc, the kinetic energy peaks 8×10^6 years after minimum separation and the galaxies are in their most contracted state a further 8×10^6 years later. Thus one might expect to observe a significant increase in the star formation rate about 10^7 years after the first passage of such galaxies. The timescale for merger of these galaxies (about 10^9 years) is not the relevant one for the initiation of star formation.The larger and smaller galaxies in an interacting system have different dynamical time scales which may lead to bursts of star formation at different times in a pair, typically 10^7 to 10^8 years apart. This may explain why some pairs of interacting disk galaxies exhibit very different current star formation characteristics (6).

Some interacting systems, such as UGC 12914/5, are observed to have large HII regions far away from either nucleus. These systems may be explained as the result of an interpenetrating collision of two disk galaxies in which a high density was obtained part way between the two nuclei. If the angular momentum and kinetic energy roughly cancel then a somewhat detached star forming region may result. We see evidence of this possibility in some of our collision models. Interacting counter rotating disks may help reduce the total angular momentum of the gas in interacting systems and thus allow the gas to spiral in towards the nuclei and accumulate there. Strong density enhancements are found in the disk particles during collision, and these are often in the form of strong, if temporary, linear (bar-like) features. The existence of such features in real systems appears correlated with high rates of star formation.

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P3. Dynamical Experiments on models of colliding disk galaxies.

R. A. Gerber, D. S. Balsara, and S. A. Lamb.

From 'Paired and Interacting Galaxies', IAU Colloquium 124, J. W. Sulentic, W. C. Keel, C. M. Telesco (Eds.), NASA Scientific and Technical Information Division, p. 737, 1990.