The title “Dynamics of Mergers” seems broad enough to cover a daunting range of topics. To make things more manageable, I will focus the discussion here on the type of mergers which are largely thought to give rise to the subject of this workshop – the ultraluminous infrared galaxies (ULIRGs). Because of their morphologies and gas contents, ULIRGs are believed to arise from mergers of two comparable mass, gas-rich spiral galaxies – this will define the “merger” part of the title. The “dynamics” involved will be largely the gravitational dynamics of merging, and the dynamics of gas inflows which fuel the central activity in ULIRGs, be it starburst or AGN.

1. The Life of a Merger

To begin a discussion of merger dynamics, it is perhaps best to describe the different dynamical phases of the merging process. Figure 1 shows a “typical” merger (described in detail in Mihos & Hernquist 1996 [MH96]) involving two equal mass disk galaxies colliding on a parabolic orbit with perigalactic separation of $2.5h$, where $h$ is the exponential disk scale length. One disk is exactly prograde, while the other is inclined 71° to the orbital plane. Both disks are embedded in truncated isothermal dark halos with mass 5.8 times the disk mass. The half-mass rotation period is $t_{\text{rot}}$.

- **Pre-collision** $\Delta t \sim 0.01 \left( \frac{r_{\text{peri}}}{h} \right)^{3/2} t_{\text{rot}}$
  
  As the galaxies fall in towards each other for the first time, they move on simple parabolic orbits until they are close enough that they have entered each others' dark halos, and the gravitational force becomes non-Keplerian. During this infall, the galaxies hardly respond to one another at all, save for their orbital motion.

- **Impact!** $\Delta t \sim 0.3 \left( \frac{r_{\text{peri}}}{h} \right)^{3/2} t_{\text{rot}}$
  
  As the galaxies reach perigalacticon, they feel the strong tidal force from one another. The galaxies become strongly distorted, and the
tidal tails are (appropriately!) launched from their back sides. Strong shocks are driven in the galaxies’ ISM due to tidal caustics in the disks as well as direct hydrodynamic compression of the colliding ISM.

- **(Self-) Gravitational Response** $\Delta t \sim t_{\text{rot}}$
  As the galaxies separate from their initial collision, the disk self-gravity can amplify the tidal distortions into a strong $m = 2$ spiral or bar pattern. This self-gravitation response is strongly coupled to the internal structure of the galaxies as well as their orbital motion, resulting in a variety of dynamical responses (see §3).

- **“Hanging Out”** $\Delta t \sim ?$ – long? short?
  Having plowed through the densest parts of one another’s dark halos, the galaxies experience strong dynamical friction, causing the orbit to decay. The galaxies linger at apogalacticon for a significant time (several to many rotation periods) before falling back together and merging. The timescale here is crucially dependent on the distribution of dark matter at large radius, resulting in significant uncertainties in the duration of this phase (see §5).

- **Merging** $\Delta t \sim \text{a few } t_{\text{rot}}$
  Once the galaxies fall back together, they typically dance around each other once or twice more on a short-period, decaying orbit before coalescing into a single remnant. During this period, gravitational torques and hydrodynamic forces are strong, resulting in strong gaseous inflow and rapid violent relaxation.

- **Relaxation** $\Delta t \sim \text{a few } t_{\text{rot}}(R)$
  Once the galaxies merge, a general rule of thumb is that violent relaxation and/or dynamical mixing occurs on a few rotation periods at the radius in question. In the inner regions, the remnant will be relaxed in only $\sim 10^8$ yr; in the outer portions mixing may take $> 10^9$ yr.

2. **Where are the ULIRGs?**

Given this range of dynamical states, it is useful to ask which state preferentially hosts ULIRG galaxies. The fact that they are predominantly close pairs or single, disturbed systems argues that late stage systems dominate, but can we be more quantitative? Such insight can come from an analysis of the projected separations of ULIRGs (e.g., Murphy et al. 1996). If we know the orbital evolution of binary galaxy pairs, we can statistically reconstruct the distribution of dynamical phases from the observed projected separations. In essence, this exercise will reveal how ULIRG activity samples the general merging population.
This selection function can be determined (in an admittedly model-dependent fashion) using N-body simulations of merging galaxies. A suite of merger models is calculated, focusing on the close ($r_{\text{peri}} = 2, 4, 6, 8, \text{and} 10$ disk scale lengths), equal-mass mergers thought to give rise to ULIRGs. Given the orbital evolution of these models, we “observe” the model pairs randomly in projection, and weighted by $r_{\text{peri}}^2$ (geometric weighting of orbits). Because the merging timescale differs drastically in mergers of different impact parameter, we define a relative timescale as $t_{\text{rel}} = t/t_{\text{merge}}$ in which initial impact occurs at $t_{\text{rel}} = 0$ and final merging occurs at $t_{\text{rel}} = 1$.

If we “observe” the merger models completely randomly in time – in essence assuming the the ULIRG selection function is constant over dynamical stage – we construct the histogram of projected separation $\Delta R$ shown in Figure 2a. Because binary galaxies spend most of their orbital lifetimes at apogalacticon, and because distant encounters are assumed to be more common than close ones, $N(\Delta R)$ shows a strong peak at extremely wide
Figure 2. Monte Carlo “observations” of merger models. If orbital time is sampled uniformly (bottom left), the distribution of projected separation is strongly weighted to distant pairs (upper left). To match the observed distribution of ULIRG separations (upper right, from Murphy et al. (1995); hatched regions represent upper limits), ULIRGs must be strongly biased towards late stage mergers (bottom right). See text for details.

separations, $\Delta R > 30$ kpc. As this is far from the observed situation, a flat selection function (Fig 2c) is clearly unrealistic. However, from this histogram, we can do a Monte Carlo rejection of observations in each bin until we match the true observed $N(\Delta R)$ histogram (Fig 2b). At this point, we can determine from the models the distribution of dynamical ages of the surviving observations (Fig 2d). From this distribution, we see that ULIRGs must come predominantly from mergers in the final 20% of their merging history – in other words, the final merging phase. A small fraction of objects may come from objects near their initial collision. This selection function argues that galaxies are somehow stable against the onset of ULIRG activity over most of the merging history, even though they respond dynamically at a much faster pace. What, then, causes this disconnect between dynamical response and ULIRG activity?

3. Is there a Dynamical Trigger?

Whatever powers the extreme luminosity of ULIRGs, the requisite is sufficient fuel in the form of interstellar gas. From a dynamical point of view, the link between ULIRG activity and the merging process must lie in the
detailed dynamics which drive nuclear gas inflows in mergers. Is there a
distinct dynamical trigger which begins this inflow and resultant ULIRG
activity, or are there several paths to the formation of ULIRGs?

3.1. THEORETICAL EXPECTATIONS

Much of our understanding of the dynamical triggering of inflows in galaxies
comes from N-body simulations. These simulations have generally shown
that gaseous inflows in galaxies arise largely in response to the growth of
$m = 2$ instabilities in disks – spiral arms or, more strongly, bars (Noguchi
1988; Barnes & Hernquist 1991; MH96; BH96). As such the question of
inflow triggers becomes one of bar instability in disks. What kind of en-
counters drive bars? When in the merging sequence do they form?

A variety of simulations have revealed a variety of answers. In disks
which are susceptible to global instabilities, strong bars form shortly after
the initial collision. In these situations, rapid inflow occurs within a few disk
rotation periods, providing the fuel for early starburst or AGN activity well
before the galaxies merge (MH96, BH96). If these types of galaxies were
the dominant sources for ULIRGs, ULIRG samples should contain many
more wide pairs than are actually observed. Disk stability, therefore, may
be one criterion for forming ULIRGs.

That stability may come from the presence of a massive central bulge or
a low ratio of disk-to-dark matter in the inner disk. Simulations by Mihos
& Hernquist (1994, MH96) show that a bulge component can stabilize the
disk against bar formation, holding off inflow until the galaxies ultimately
merge. At this point the strong gravitational torques and gasdynamical
shocks overwhelm any stability offered by the bulges, and the gas is rapidly
driven inwards on a dynamical timescale, presumably fueling a starburst or
active nucleus. In interesting contrast to these models are those of Barnes &
Hernquist (1996, BH96) which employed a similar 3:1 disk-to-bulge ratio in
their model galaxies, but with a much lower density bulge. In these mod-
els, the bulges were unable to stabilize the disks, and early inflow again
occurred. Clearly it is thus more than the mere presence of bulges that
stabilize disks – the bulges must be sufficiently concentrated that the dom-
inate the mass distribution (and thus the rotation curve) in the inner disk.
Alternatively, a high fraction of dark-to-disk mass in the inner portion of
the galaxies may also stabilize the disks; such is probably the case in low
surface brightness disk galaxies (Mihos et al. 1997).

Aside from internal dynamics, the orbital dynamics also play a role
in triggering inflow and activity. BH96 also show how orbital geometry
influences the inflow and activity. For galaxies with a modest amount of disk
stability, a prograde encounter will be sufficient to drive bar instabilities,
while a retrograde encounter will not. In these cases, retrograde disks will survive the initial impact relatively undamaged, and not experience any strong activity until the galaxies ultimately merge. In the extreme situation of very strong or very weak stability, however, internal stability effects tend to win out over orbital effects (MH96).

More recently, simulations have shown that triggering of activity may not be solely tied to the physics of inflows. Instead, the fueling of activity may be moderated by starburst energy, which can render the gas incapable of forming stars. Simulations by Gerittsen (1998) indicate that a starburst can heat a significant fraction of the inflowing gas to a few million degrees; the onset of star formation in this gas must await radiative cooling, resulting in milder but longer-lived starbursts compared to those of MH96. With the current uncertainties in modeling the physics of star formation and starburst feedback, this result does not bode well for the detailed predictive power of any current starburst merger model.

3.2. OBSERVATIONAL CONSTRAINTS

While the dynamical models can guide our expectations, the variances due to effects such as galactic structure, orbital geometry, and starburst physics make it hard to isolate any single effect as a dominant trigger. Can we instead turn to the observational data to complement these models? Because of the rapid decoupling of the nuclear gas from the global kinematics, studies of nuclear kinematics may give an improper account of the dynamical history of the encounter. Instead, global kinematics have a better “memory” of the initial conditions and evolution of the collision.

To study these global kinematics, Mihos & Bothun (1998) recently examined the two dimensional $H\alpha$ velocity fields of four southern ULIRGs. These galaxies were chosen to display extended tidal features, and thus biased the sample towards largely prograde systems. Nonetheless, the four systems showed a wide range of kinematic structure, with no distinct commonality. One (IRAS 14348-1447) showed short tidal features, extended $H\alpha$ emission, and fairly quiescent disk kinematics, suggesting the system is a young interaction. The second (IRAS 19254-7245, the Superantennae) possessed extremely long tidal features, more concentrated $H\alpha$ emission, and evidence for outflowing winds – clearly a more advanced interaction, although the pair is still separated by $\sim 10$ kpc and simple disk kinematics still dominate the overall velocity field. IRAS 23128-4250 is the most distorted of the four, with two nuclei separated by $\sim 4$ kpc, several distinct overlapping kinematic components, and a $90^\circ$ slew in the angular momentum vector of the system from the nuclear regions to the extended tidal features. Such kinematic structure cannot survive for long, so we must be
catching IRAS 23128-4250 in a very transient stage associated with the final merging. Finally, the fourth system (IRAS 20551-4250) consists of a single nucleus in an r^{1/4} galaxy with a single long tidal tail. The Hα is very centrally concentrated, and shows simple rotational motion indicative of the quiescent dynamical stage following the completion of the merger. The fact that we see four ultraluminous systems in four very different dynamical phases argues that (at least in this small sample) there is no common dynamical trigger for ULIRG activity. A similar conclusion was reached by Hibbard & Yun (1996) from a study of the HI morphologies of ULIRGs, which showed no tendency towards prograde interactions.

We are left then with a bit of a dissatisfying – although perhaps not unexpected – result. Both theoretical and observational arguments indicate there is no unique trigger for ULIRG activity. While ULIRGs are associated with late stage mergers, beyond that there seems to be no one-to-one mapping of dynamics to ULIRG activity. Internal structure, orbital dynamics, gas content, and starburst physics must all play competing and tangled roles in the ultimate triggering of ULIRG activity.

4. The Believability of N-body Models

Given the ever-expanding role numerical simulation plays in the study of galactic dynamics, and in particular galaxy mergers, it is perhaps prudent here to make a few critical comments on the robustness of N-body modeling. With respect to the ULIRG question, the first obvious shortcoming of the current generation of N-body models is numerical resolution. The spatial resolution of models such as those of MH96 or BH96 are \( \sim 100 \) pc, many orders of magnitude larger than any central accretion disk.\(^1\) While these models have shown the efficacy of mergers at driving radial inflows, they cannot address accretion onto an AGN, other than the first step of fueling gas inwards from the disk. This is no trivial matter – to reach the accretion disk the gas must shed several orders of magnitude more angular momentum (e.g., Phinney 1994). Ideas with which to mediate this further inflow abound, such as nuclear bars (Shlosman et al. 1990), dynamical friction (Heller & Schlosman 1994), or gravitational torques (Bekki 1995). While invoking such processes is quite reasonable, we must realize that in the context of AGN triggering these arguments remain purely speculative, and cannot be resolved in present models.

Modeling of the nuclear dynamics of mergers is both a technical and physical challenge. First, because the resolution scales with the mean in-
terparticle separation ($\langle r \rangle \sim N^{1/3}$), to get a factor of two improvement in resolution demands an order of magnitude increase in the number of particles (and CPU time) employed. However, sheer brute force will not solve the problem – on these smaller scales the starburst and AGN physics begin to dominate the dynamical equations. To see this, equate starburst power to binding energy for a $M_g = 10^{10} M_\odot$, $10^{12} L_\odot$, $10^7$ year starburst inside 100 pc:

$$\epsilon L \Delta t = \frac{GM_g^2}{R}$$

$$\epsilon 10^{60} = 10^{59}$$

If the efficiency of energy deposition into the ISM ($\epsilon$) is even a few percent, it can have a significant effect on the nuclear gasdynamics. Star formation and feedback remains poorly understood, and efforts to incorporate it into dynamical simulations are fraught with uncertainties – this problem stands as the biggest obstacle in modeling the dynamical evolution of ULIRGs. Until better models exist for incorporating feedback into N-body simulations, improved spatial resolution is meaningless.

What, then, can we believe from N-body simulations? Surely the gravitational dynamics are well understood, right? They are, up to a point. Unless Newtonian mechanics are wrong, N-body models accurately calculate the gravitational forces acting on the merging galaxies. The uncertainties lie not in the physics of gravity, but in the initial conditions of the model, in particular the mass distribution of the different components of the galaxies. The dynamics of inflow are dependent on the mass distribution in the inner disk, but are disk galaxies maximal disks? Minimal disks? Equally problematic is the strong dependency of the merger evolution on the distribution of dark matter at large radius, which affects the orbital evolution and merging timescale. As we shall see next, these uncertainties make even pure gravitational modeling of merging galaxies uncertain.

5. The Role of Dark Matter

Dark matter halos play the dominant role in determining the dynamics of merger on large (tens of kpc) size scales. On these scales, it is the dynamical friction of the dark halos which brakes the galaxies on their orbit and causes them to merge. Different dark matter halos lead to different orbital evolution and merging timescales for the colliding galaxies. With the amount of dark matter in galaxies poorly constrained, particularly at large distances from the luminous disks, these effects represent a serious uncertainty in dynamical modeling of galaxy mergers. While recent cosmological simulations give detailed predictions of the dark matter distribution on large scales (e.g., Navarro et al. 1995), these predictions are at often at odds with observed galaxy rotation curves (McGaugh & de Blok 1998).
Most models of galaxy mergers to date have typically employed relatively low mass dark halos truncated outside of a few tens of kpc. More recently, efforts have been made to include more massive and extended halos in merger models. While results on the detailed evolution of the tidal debris remain contentious (Dubinski et al. 1996, 1999; Barnes 1998; Springel & White 1998), one thing is clear – the more massive the dark halo is, the longer the merging time. At first this may seem counter-intuitive, since the more “braking material” there is, the faster the braking ought to be! But halo mass also provides acceleration, so that galaxies with more massive halos are moving faster at perigalacticon, diminishing the efficiency of dynamical friction. At fixed circular velocity, the higher encounter velocity wins out over the increased dynamical friction, and merging time increases. This can be seen in Figure 3, which shows the orbital evolution of two equal-mass mergers, both with similar rotation curves in the luminous portion of the galaxy, but where one has a dark matter halo three times the mass of, and twice as extended as, the other.

The differences in orbital evolution among models with different dark halos have several ramifications for merger dynamics and the formation of ULIRGs in particular; for example:

− **Timing of inflows:** In §2, statistical arguments were made that the onset of activity is largely suppressed over 80% of the merger evolution, and that inflow occurs only late. If in fact halos are even more massive, and the merging timescale even longer, this constraint becomes even more severe – over more than 95% of the merger timescale the galaxies must lie dormant before activity is triggered. In this case, the dynamical stability must be strong indeed.

− **Modeling of specific systems:** The rapid advances in N-body modeling have made it easy to construct “made-to-order” models of specific systems. However, uncertainties in the dark matter distribution translate in significant uncertainties in the dynamical evolution of mergers inferred from these models. For example, dynamical models of NGC 7252 can be constructed using a variety of halo models (Mihos et al. 1998), all of which successfully reproduce the observed kinematics of the system, yet have orbital characteristics and merging timescales which differ significantly. These uncertainties argue that such specific models are caricatures of the real systems, and that inferences of the detailed dynamics of specific systems based on such models are ill-motivated.

### 6. High-z Musings

Finally, in light of the new results from SCUBA on possible high redshift analogs of nearby ULIRGs (e.g., Smail et al. 1998; Barger et al. 1998), it is
interesting to ask how any of the lessons we have learned apply to mergers at higher redshift. The first immediate question is: are these SCUBA sources disk galaxy mergers at all? The “smoking gun” of a disk merger is the presence of tidal tails, but such features will be difficult to detect. The surface density of these structures evolves rapidly, giving them a dynamical lifetime which is short – ∼ a few \( t_{\text{rot}}(R) \). Only outside of \( \sim 10 \) kpc are tidal features long-lived, yet here their surface brightness is quite faint (\( \mu_R \gtrsim 25-26 \) mag arcsec\(^{-2}\)). Add to this the \((1 + z)^4\) cosmological dimming, and by \( z = 2 \) the surface brightness of these features will be down to 30–31 mag arcsec\(^{-2}\), very hard indeed to detect. In fact, with the tidal features so faint and the inner regions perhaps highly obscured, simply detecting these galaxies may be quite problematic, much less determining their structural and dynamical properties.

Nonetheless it is instructive to ask how disk mergers might evolve differently at high redshift compared to present day mergers. High redshift disks may well have been more gas-rich than current disk galaxies, resulting in more fuel for star formation and in a lower disk stability threshold (the Toomre \( Q \)). As a result, rather than driving gas inwards, collisions of galaxies at high redshift may instead result in pockets of disk gas going into local collapse and increasing disk star formation at the expense of nuclear starbursts. Morphologically, we might expect mergers to show an extended, knotty structure of sub-luminous clumps rather than an extremely luminous, nucleated structure. Qualitatively this is similar to the types of objects found in the Hubble Deep Field(s), where multiple bright knots observed in the restframe UV may be embedded in a single structure when observed in rest frame optical. We should therefore apply extreme caution when applying results obtained from merger models based on nearby galaxies to the high redshift universe.
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