LOPSIDED GALAXIES AND THE SATELLITE ACCRETION RATE

DENNIS ZARITSKY
UCO/Lick Observatory and Univ. of Calif. Santa Cruz
Santa Cruz, CA, USA

AND

HANS-WALTER RIX
Steward Observatory
Univ. of Arizona, Tucson, AZ, USA

1. Introduction

Although current observations and theoretical models indicate that galaxy mergers and interactions are catalysts in the process of galaxy evolution, we have only a limited quantitative understanding of some basic aspects of the process. For example, the rate at which galaxies merge is poorly constrained. We can simplify the problem by considering only disk galaxies, which because of the fragility of their disks (cf. Tóth and Ostriker 1992) have presumably not suffered a major merger. Even so, these galaxies have almost certainly experienced the infall of small companion galaxies at some time. The Milky Way is currently experiencing the accretion of the Sagittarius dwarf (Ibata, Gilmore, & Irwin 1994) and will eventually accrete the Magellanic Clouds (Tremaine 1976). To understand how galaxies evolve, we need to have quantitative knowledge of the accretion rate as a function of mass for all types of galaxies. Here we consider only the accretion of companion galaxies ($\sim$ 10% by mass) onto large spiral galaxies.

How can we measure the accretion rate of small companion galaxies onto large spirals? First, we identify a signature of the accretion event. Second, we measure the frequency of the signature among a carefully chosen set of galaxies. Third, we derive the lifetime of such a signature after the accretion event. By combining the frequency and duration of the signature, we then calculate the accretion rate. In this paper, we describe such a calculation done by attributing disk lopsidedness to the relatively recent accretion of

J.E. Barnes and D.B. Sanders (eds.), Galaxy Interactions at Low and High Redshift, 117–124.

a moderate mass satellite. Because lopsidedness is not necessarily uniquely associated with accretion, such an estimate will result in an upper limit on the accretion rate. Future work, which combines several signatures and more detailed dynamical modeling of the various processes that may create the signature, will lead to improved measurements. The results and techniques described here are presented in a series of papers (Rix & Zaritsky 1995; Zaritsky 1995; Zaritsky & Rix 1997).

2. Lopsidedness in Spiral Galaxy Disks

The candidate signature for lopsidedness must be a relatively simple quantity that is easy to measure and robust to minor variations in galaxy type, inclination, luminosity, and surface brightness. This leads one to low order distortions. The most global of these is an $m = 1$ distortion, or lopsidedness. The ubiquity of lopsidedness was first noted by Baldwin, Lynden-Bell, and Sancisi (1980) and then studied in HI line profiles by Richter & Sancisi (1994). We will focus on lopsidedness in the stellar component. The advantage of using the stellar component is that the stars trace lopsidedness at smaller radii, where lopsidedness is more quickly dynamically erased and so provides a finer chronometer of the interaction.

The measurement of lopsidedness in disk galaxies is done photometrically. We decompose the light in circular annuli into a Fourier series in position angle. For the purpose of this presentation, we only discuss the amplitudes of the $m = 0$ and 1 terms, although higher order terms are interesting for other reasons. We quantify lopsidedness by referring to the average of the ratio of the amplitude of the $m = 1$ term, A_1, to the amplitude of the $m = 0$ term, A_0, between 1.5 and 2.5 disk scale-lengths. This quantity is referred to as $\langle A_1 \rangle$.

We observed a sample of nearly face-on disk galaxies, brighter than $m_B = 13.5$, with relative velocities $V < 5500$ km s^{-1}, and with kinematic inclinations less than 32°. The kinematic inclination is determined by inverting the Tully-Fisher relation and comparing to the observed HI line-width. Our data consist of I(0.8μm) and K$'$(2.2μm) images, although not both for all of the galaxies. The exposure times are short (15 min in I and 30 on-object in K$'$), so obtaining the data is straightforward. The measurement of lopsidedness is consistent between the two bands (Zaritsky & Rix 1997). The final sample consists of 60 galaxies.

The distribution of $\langle A_1 \rangle$ is nearly uniform between 0 and 0.25, with a few galaxies beyond 0.25 (cf. Fig. 1). We have chosen somewhat arbitrarily $\langle A_1 \rangle \geq 0.2$ to denote galaxies that are "significantly" lopsided. We will adopt this as the definition for the rest of the discussion; however, more detailed treatments of this issue must consider the distribution of $\langle A_1 \rangle$

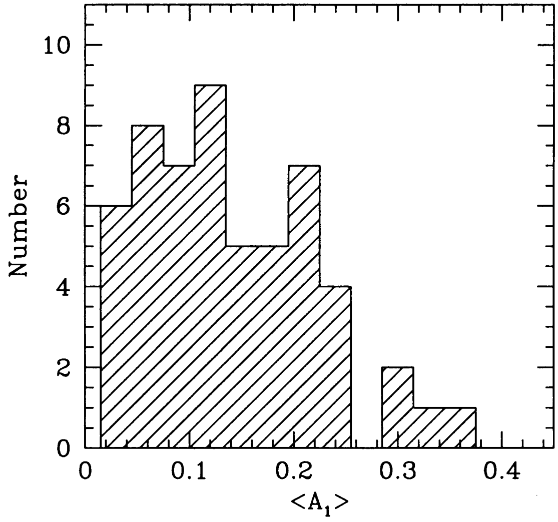

Figure 1. The distribution of the lopsidedness parameter, $\langle A_1 \rangle$. This distribution is drawn from the combined I and K′ data.

rather than simply modeling the number of galaxies beyond the threshold.

Nearly one-third of the spirals in our sample of 60 have $\langle A_1 \rangle > 0.2$. If we can associate such large lopsidedness with accretion events then we can begin to measure the accretion rate.

3. Accretion and Lopsidedness

Is the level of lopsidedness observed consistent with the infall of a moderate (10% by mass) satellite? Simulations of such an infall event were performed by Walker, Mihos, and Hernquist for the infall of a satellite onto a disk galaxy. In this simulation the satellite has 10% of the mass of the disk of the parent (1% of the total mass of the parent). Such a system is comparable to the LMC/MW system. In the simulation the parent has $\langle A_1 \rangle$ (measured in the same manner as for the data) that is 0.25 ± 0.03, 0.22 ± 0.02, and 0.18 ± 0.01 at times 1, 1.125 and 2.5 Gyr after the beginning of the simulation (at which time the satellite is at a radius of 6 disk scale lengths on an orbit inclined 30° to the disk plane).

This single simulation demonstrates that the accretion of a small companion is a plausible mechanism for generating lopsidedness of the observed magnitude. However, a variety of simulation parameters (involving different mass ratios, orbital angular momentum, and orbital inclination) must

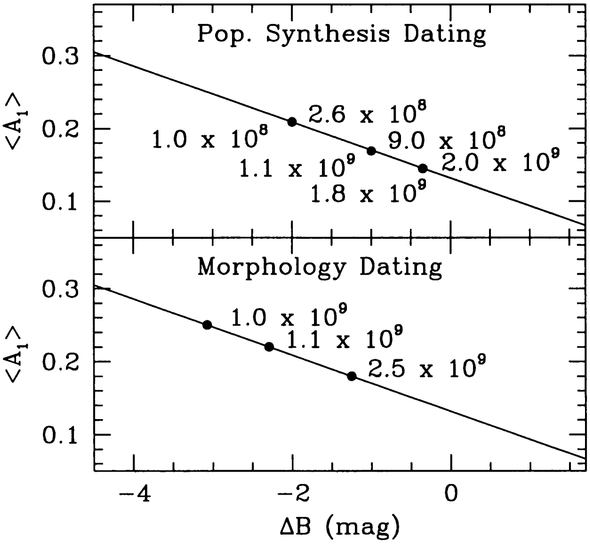

Figure 2. Comparison of the estimated chronology using the population synthesis models (see §4) and the dynamical simulation described in this section. For the population synthesis ages above the line come from the 0.5 Gyr burst models and the ages below come from the 0.1 Gyr burst model.

be considered to derive the expected distribution of lopsidedness. In addition, it is likely that other phenomenon will also generate lopsidedness. For example, close interactions between galaxies may generate lopsidedness of a similar magnitude as the infall of a small companion (Weinberg 1994). Others have examined dynamical instabilities as the source of lopsidedness (cf. Weinberg 1994; Sellwood & Valluri 1997). Currently, the incidence of lopsidedness can only be taken as a possible indication of an accretion event.

The simulations also allow us to measure the lifetime of significant distortions, and therefore obtain the third piece of information required to measure the accretion rate. However, further exploration of parameter space is also critical here. In the one simulation available so far, the lopsidedness parameter remains above 0.2 for about 1 Gyr (Fig. 2). Combining the fraction of spirals that exhibit such lopsidedness ($\sim$ 0.3) with the lifetime ($\sim$ 1 Gyr) implies that an accretion event happens at most once every three Gyr for the typical field spiral galaxy. However, as we discuss next, this result may be biased high.

4. Luminosity Enhancement as a Chronometer and Possible Bias

Interactions among massive galaxies are known to enhance star formation activity (Larson & Tinsley 1987; Lonsdale, Persson, & Mathews 1984; Kennicutt et al. 1987; Lavery & Henry 1988). Therefore, it is plausible to conjecture that the accretion of a small satellite might do the same. If so, then our *magnitude limited* sample of galaxies would be biased in favor of systems that have recently accreted a satellite and hence brightened. We discuss that possible bias below, but first discuss how a triggered starburst can be used to determine the time since the interaction.

We have used Bruzual & Charlot (1993) stellar population models to place limits on how the galaxy colors will change during 10% burst (*e.g.*, 10% of the stars in the galaxy were born during the interaction). In the models presented here, we assume that the underlying galaxy light is dominated by an old population of stars (models with a base of younger stars show less pronounced changes in both the color and $M_{\rm B}$). From such models we can predict the change in both the $B-R$ color and in $M_{\rm B}$ as a function of time since the triggered burst (Fig. 3).

From the dynamical simulation we can determine the relationship between the time since the accretion event and lopsidedness, and from the stellar synthesis models we can determine the relationship between the time since the burst and lopsidedness. If we can connect the accretion event with the burst (*e.g.*, the burst happens 100 Myr after the accretion) then we can synchronize the two chronometers and use the two to measure the time elapsed since the accretion event and to check the results. The inferred ages from each method are shown in Fig. 2 — assuming that the starburst begins at the same time as the dynamical simulation.

We have searched for signs of a connection between recent star formation and lopsidedness by defining a "blue" color as the galaxy's deviation from the B-band Tully-Fisher relation. There is a marginally significant correlation, in the expected sense, between this color and the lopsidedness measurement. If a line is fit to this relationship, and the effective search volumes for normal and lopsided galaxies are calculated, then we find that we have effectively searched for lopsided galaxies in a volume that is four times larger than that searched for normal galaxies. This difference in search volumes causes a corresponding decrease in our estimate of accretion rate. Hence, it is evident that either one must obtain volume limited samples, or have an excellent understand of the degree of brightening of a galaxy during an interaction.

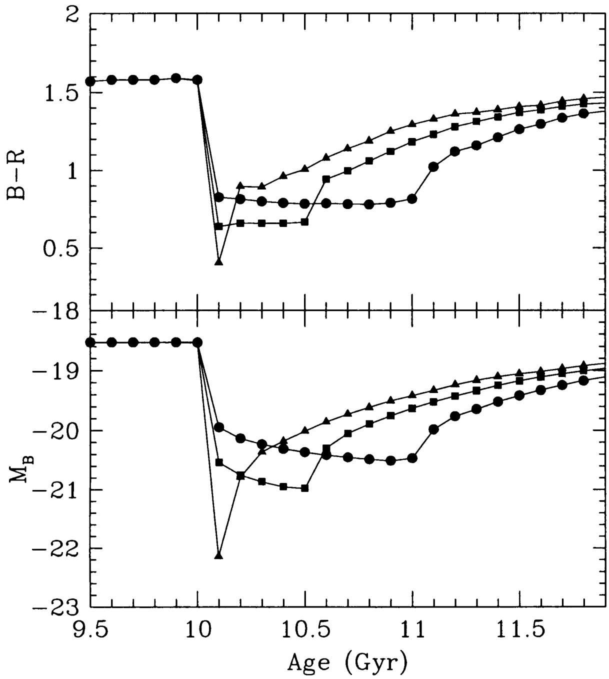

Figure 3. The effect of a 10% starburst on the color and luminosity of the galaxy. Three models are plotted: a 1.0 Gyr burst model (filled circles), a 0.5 Gyr burst model (filled squares), and a 0.1 Gyr burst model (filled triangles).

5. Directions Toward Progress

This work described here is a first attempt to use lopsidedness to measure the accretion rate. There is potential in the method, even though there are clear avenues for progress. First, we should obtain a volume limited sample to eliminate the issue of brightening due to the interaction. Second, we should obtain a sample of early type galaxies to determine the Hubble-type lopsidedness connection. Ongoing work by Rudnick and Rix (1997, *in prep.*) show that the fraction of highly lopsided galaxies is nearly the same in early type spirals ($\sim$ 20%). Third, we should examine a larger suite of simulations to determine the variations in lopsidedness created by different accretion events. This is being done by Velazquez, Dubinski, and Zaritsky. Fourth, we need to understand alternative phenomena that generate $m = 1$ distortions.

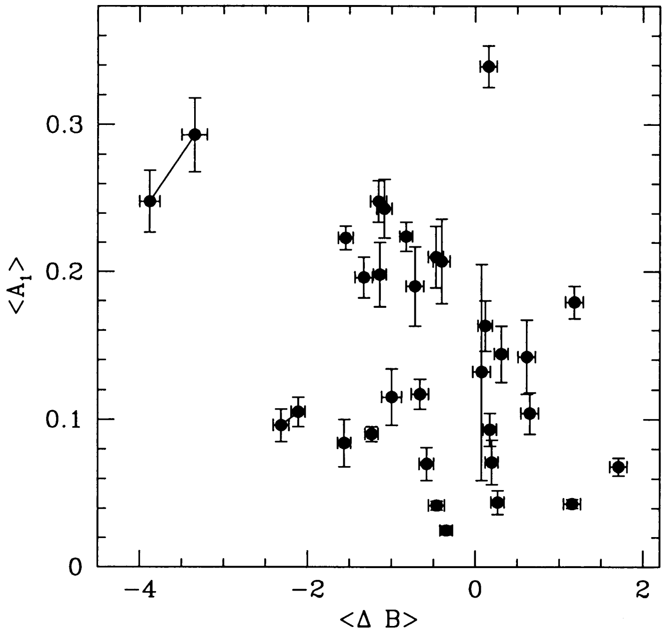

Figure 4. Color vs. Lopsidedness. We plot the mass-weighted color, $\langle \Delta B \rangle$, vs. the lopsidedness parameter, $\langle A_1 \rangle$. The two pairs of points connected by a line indicate the different measurements obtained for the same galaxies in I and K′ and with slightly different adopted parameters.

6. Summary

The accretion rate can be constrained by identifying a signature of accretion and measuring the frequency and lifetime of that signature. We have used disk lopsidedness as that signature. We estimate that the accretion rate is between 0.07 and 0.25 satellites per Gyr for satellites that are about 10% of the mass of the spiral disk.

References

Baldwin, J., Lynden-Bell, D., & Sancisi, R., (1980), *MNRAS*, **193**313
Bruzual, A. G., & Charlot, S. (1993), *ApJ*, **405**, 538
Ibata, R.A., Gilmore, G., & Irwin, M.J. (1993), *Nature*, **370**, 194
Kennicutt, R.C. et al. (1987), *AJ*, **93**, 1011
Larson, R.B., & Tinsley, B.M. (1978), *ApJ*, **370**, 194
Lavery, R.J., & Henry, J.P. (1988), *ApJ*, **330**, 596
Lonsdale, C., Persson, S.E., & Mathews, K. (1984), *ApJL*, **287**, 95L
Richter, O., & Sancisi, R (1994), *AA*, **290**, 9
Rix, H.-W., & Zaritsky, D. (1995), *ApJ*, **447**, 82
Sellwood, J.A., & Valluri, M. (1997), *MNRAS*, **287**, 124

Tóth, G., & Ostriker, J.P. (1992), *ApJ*, **389**, 5
Walker, I.R., Mihos, J.C., & Hernquist, L.(1996), *ApJ*, **460**, 121
Weinberg, M. (1994), *ApJ*, **421**, 481
Zaritsky, D., & Rix, H.-W. (1997), *Ap.J.*, **448**, L17
Zaritsky, D., & Rix, H.-W. (1997), *Ap.J.*, **477**, 118