The Masses of Distant Galaxies from Optical Emission Line Widths

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Abstract. Promising methods for studying galaxy evolution rely on optical emission line width measurements to compare intermediate-redshift objects to galaxies with equivalent masses at the present epoch. However, emission lines can be misleading. We show empirical examples of galaxies with concentrated central star formation from a survey of galaxies in pairs; HI observations of these galaxies indicate that the optical line emission fails to sample their full gravitational potentials. We use simple models of bulge-forming bursts of star formation to demonstrate that compact optical morphologies and small half-light radii can accompany these anomalously narrow emission lines; thus late-type bulges forming on rapid (0.5 – 1 Gyr) timescales at intermediate redshift would exhibit properties similar to those of heavily bursting dwarfs. We conclude that some of the luminous compact objects observed at intermediate and high redshift may be starbursts in the centers of massive galaxies and/or bulges in formation.

1 Introduction

Optical emission line widths are potentially important diagnostic tools for measuring the intrinsic gravitational masses of galaxies within their optical radii. Because of the sensitivity requirements for spatially resolved rotation curves, large surveys of galaxies at intermediate redshift and studies of galaxies at high redshift use unresolved or “integrated” emission line widths, computed from Gaussian fits to emission lines in the spectrum of the whole galaxy. However, the results are sometimes ambiguous in the case of compact star-forming galaxies.

The luminous compact blue galaxies observed at intermediate redshift (e.g., Koo et al. 1994; 1995) have small half-light radii ($R_e = 1 – 3.5$ kpc) and narrow emission-line velocity widths ($35 < \sigma < 126$ km s$^{-1}$). These properties suggest that although they are luminous galaxies, compact blue galaxies may be intrinsically faint galaxies undergoing a strong burst of star formation (Guzmán et al. 1996; 1997). However, Kobulnicky & Zaritsky (1999) measure high metallicities for these objects, appropriate only for massive galaxies, and HST images show possible evidence for surrounding older populations (Guzmán et al. 1998). Similarly, at higher redshifts ($z \sim 3$) the “Lyman break” galaxies also exhibit narrow integrated line widths that do not correlate with galaxy luminosity (Pettini et al. 2001). These observations taken together raise the question of whether emission
line widths of compact objects accurately trace their potential wells (Kobulnicky & Zaritsky 1999).

We present evidence from observations of local galaxies and simple models of compact star formation that centrally concentrated star formation changes the measured emission line widths and half-light radii of galaxies (see also Kobulnicky & Gebhardt 2000; Pisano et al. 2001). This star formation can arise from major mergers (Mihos & Hernquist 1996), minor mergers (Mihos & Hernquist 1994), and secular evolution (Pfenniger & Norman 1990), processes that may be directly linked to bulge formation. The number of compact blue objects at intermediate redshift that are actually concentrations of star formation in larger galaxies remains unknown. If the luminous, compact blue galaxies are frequently bulges in formation, their number counts contain information about the timescales for evolution along the Hubble sequence.

2 Local Galaxies with Compact Central Star Formation

In a recent spectroscopic study of the centers of 502 galaxies in pairs, Barton, Geller, & Kenyon (2000) find evidence for correlations between the star-forming properties of interacting galaxies and the pair separations on the sky and in recession velocity. Their observations are broadly consistent with the Mihos & Hernquist (1996) picture of close galaxy-galaxy passes triggering gas infall and subsequent star formation in the central regions of some galaxies. Barton et al. (2001) examine the Tully-Fisher properties of a subset of the paired galaxies and find four galaxies that are apparently overluminous outliers to the relation. Barton & van Zee (2001) present VLA HI observations of two of the outliers; the radio line widths of the galaxies are substantially broader than their resolved optical emission line rotation curves. Thus, the observations support the possibility that centrally-concentrated star formation can give rise to anomalously narrow emission line widths that do not reflect the full gravitational potentials of the galaxies.

Fig. 1 shows one of the Barton et al. (2001) outliers, CGCG 132-062. The top panel shows the morphology of CGCG 132-062, including the disk surrounding the central, luminous region. The bottom panel shows the major-axis longslit spectra on the same scale. The emission is not spatially extended; it is confined to the central region of the galaxy and does not include the disky outskirts.

At higher redshifts, cosmological surface brightness dimming may render low surface brightness emission from the outskirts of a disk invisible. Thus, for distant galaxies, the observational bias against measuring full kinematic line widths likely extends to galaxies other than the 4 outliers in the Barton et al. (2001) study. Fig. 2 shows the H-alpha emission profile of a non-outlier spiral, NGC 470, from Barton et al. (2001). The H-alpha in the center of the galaxy is brighter than the outskirts by a factor of \(\sim 100\); this central part reflects only \(\sim 50\%\) of the kinematic width of the galaxy. An integrated line profile and perhaps even a 2-dimensional resolved rotation curve would miss this flux and therefore result in an anomalously small line width.
Fig. 1. CGCG 132-062, an interacting galaxy with centrally-concentrated optical emission line flux. We show top a B-band image and bottom a longslit spectrum on the same scale, where the horizontal direction is the spatial direction and the vertical direction is wavelength. The emission is largely confined to the central regions of the galaxy.

3 The Effects of Centrally-Concentrated Star Formation

Large surveys frequently explore the intrinsic properties of galaxies using a limited set of structural parameters (e.g., half-light radius, $R_e$, or dispersion of fit to emission lines in the integrated spectrum, $\sigma$). However, if star formation rates vary in different components of the galaxies, the structural parameters of evolving galaxies will be affected by the differing mass-to-light ratios in the different components. In Fig. 3 we expand on the simple model of Barton & van Zee (2001) to show that a bulge-forming burst of star formation could profoundly affect the structural parameters of a galaxy during formation. Barton & van Zee (2001) describe the model in detail. We use the spectral synthesis models of Bruzual & Charlot (2001, in preparation) and typical “exponential bulge” parameters from Carollo (1999) and Courteau, de Jong, & Broeils (1996) [final $B/D = 0.1$; radius of disk is $12.5 \times$ radius of bulge]. After 7 Gyr, the previously bulge-less model spiral forms a bulge in situ in a brief period of time (instantaneous: solid line; $\tau = 0.5$ Gyr: short-dashed line; $\tau = 1$ Gyr: long-dashed line).

The top panels show that, depending on the formation timescale, the burst of star formation affects many of the basic structural parameters of the galaxy. During bulge formation, the total luminosity of the $\tau = 0.5$ or 1 Gyr models increases by < 1 magnitude, but the bulge-to-disk ratio can peak above 1 and the half-light ratio can dip to below 30% of its original value. Barton & van
Fig. 2. High surface brightness star formation in the center of a paired galaxy. We plot the rotation curve of NGC 470 top and the profile of the Hα emission incident on the slit bottom. The center is $\sim 100 \times$ higher surface brightness than the disk but reflects only $\sim$ half of the velocity width of the galaxy. Thus, although an accurate measurement at low redshift is possible, neither a high redshift spectrum nor an integrated spectrum would reflect the full velocity width of the galaxy.

Zee (2001) use same model to show that $\sigma$ for a maximal-disk rotation curve decreases to as little as 60% of its original value during bulge formation.

Although the model does not cover every possible evolutionary scenario, the results are generic and require only formation within a relatively short timescale — less than 1 Gyr — short enough to allow close galaxy-galaxy passes, minor mergers, and possibly single-episode secular evolution. With only $\sim 1 - 2$ magnitudes or less of (transient) luminosity evolution, the temporary movement in $\sigma - R_e$ space is enough to misjudge the nature of these galaxies during bulge formation (c.f., Fig. 2 in Barton & van Zee). Thus, some of the luminous compact blue galaxies observed at intermediate redshift may be intrinsically massive galaxies containing compact bursts of star formation.

4 Luminous Compact Blue Galaxies and Galaxy Evolution

The luminous compact blue objects, whether dwarfs or spirals, are clearly some of the most rapidly evolving galaxies observed at intermediate redshift. Although extreme examples of these objects are relatively rare locally, close galaxy-galaxy passes, minor mergers, and secular evolution may funnel gas into the centers of galaxies more efficiently at higher redshifts, where more gas is available.
An understanding of both dwarf and luminous galaxy evolution at intermediate redshift requires measures of their intrinsic masses and sizes, hence their $z = 0$ morphologies and luminosities. “Exponential” bulges have distinctly different properties from $R^{1/4}$-law bulges (e.g., Andredakis & Sanders 1994); they are candidates for bulges formed via secular evolution (Pfenniger & Norman 1990) or any process that sends disk gas into the center of a galaxy. If the majority of the luminous, compact blue galaxies are actually spirals undergoing strong central bursts of star formation, they may be consistent with forming exponential bulges. Thus, the fraction of these objects that are actually bulges in formation may directly reveal the “exponential” bulge formation history of the Universe.

Although existing surveys are not deep enough, deep imaging holds promise for distinguishing star formation in intrinsically low- and high-mass galaxies. Fig. 3 shows results from simulations of face-on disks at $z = 1$ in galaxies with luminous bulges. The solid lines mark the approximate limits at which accurate structural parameters measurements are possible. The points are local disks from the de Jong (1996) sample. One to two orbits with WFPC2 are only enough to characterize the higher surface brightness disks. Although the Hubble deep fields detect the majority of even face-on disks at $z = 1$, their combined area is small, containing the progenitors of few late-type galaxies at $z \leq 1$. Only upcoming ACS surveys will probe deep enough over enough area on the sky to detect the majority of disks that may surround luminous, compact blue objects at $z = 1$. 

**Fig. 3.** A simple model for a bulge-forming burst of star formation. We plot the bulge-to-disk ratio (upper left), normalized half-light radius (lower left), normalized luminosity (upper right), and total $B - R$ color (lower right) for a model spiral galaxy that forms a bulge at intermediate redshift ($T = 7$ Gyr). See the text for more details.
Fig. 4. Detection of face-on disks at $z = 1$. We plot the parameters of the de Jong (1996) spirals; solid lines show $z = 1$ limits with different WFPC2 exposures for accurate measurement of the parameters of face-on disks under luminous bulges.

References

1. Andredakis, Y. C., & Sanders, R. H. 1994, MNRAS, 267, 283
2. Barton, E. J., & van Zee, L. 2001, ApJ, 550, L35
3. Barton, E. J., Geller, M. J., & Kenyon, S. J. 2000, ApJ, 530, 660
4. Barton, E. J., Geller, M. J., Bromley, B. C., van Zee, L., & Kenyon, S. J. 2001, AJ, 121, 625
5. Carollo, C. M. 1999, ApJ, 523, 566
6. Courteau, S., de Jong, R. S., & Broeils, A. H. 1996, ApJ, 457, L73
7. de Jong, R. S. 1996, A&AS, 118, 557
8. Guzmán, R., et al. 1996, ApJ, 460, L5
9. Guzmán, R., et al. 1997, ApJ, 489, 559
10. Guzmán, R., et al. 1998, ApJ, 495, L13
11. Kobulnicky, H. A., & Gebhardt, K. 2000, AJ, 119, 1608
12. Kobulnicky, H. A., & Zaritsky, D. 1999, ApJ, 511, 118
13. Koo, D. C., Bershady, M. A., Wirth, G. D., Stanford, S. A., & Majewski, S. R., 1994, ApJ, 427, L9
14. Koo, D. C., et al. 1995, ApJ, 440, L49
15. Mihos, J. C., & Hernquist, L. 1994, ApJ, 425, 12
16. Mihos, J. C., & Hernquist, L. 1996, ApJ, 464, 641
17. Pettini, M., et al. 2001, ApJ, 554, 981
18. Pisano, D. J., Kobulnicky, H. A., Guzmán, R., & Gallego, J. 2000, in preparation
19. Pfenniger, D., & Norman, C. 1990, ApJ, 363, 391