Internal Kinematics of Galaxies at $z = 0.25–0.45$

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ABSTRACT

Low-mass starbursting galaxies have been proposed as the explanation of the excess of faint galaxies observed at intermediate redshifts. If this hypothesis is correct, then intermediate redshift galaxies should rotate more slowly than nearby galaxies with the same rest-frame luminosity. We present the results of a survey of the internal kinematics of intermediate redshift ($z = 0.25–0.45$) field galaxies to search for this effect. Using the Canada-France-Hawaii Telescope, spatially-resolved spectra of the $[\text{O II}] \lambda\lambda 3726–3729$ Å doublet emission line have been obtained for 22 galaxies. $V_{\text{rot}} \sin i$ and $[\text{O II}]$ disk scale lengths have been extracted from each galaxy spectrum using a Bayesian fitting technique.

Galaxies in the sample are found to be $\sim 1.5–2.0$ mag brighter than expected from their rotation velocity and the local Tully-Fisher (TF) relation. Low-mass galaxies exhibit a wider range of evolution relative to the TF relation than high-mass galaxies. The main source of uncertainty in this result is the large scatter in the local TF relation for late-type galaxies. Luminosity-dependent luminosity evolution neatly reconciles the lack of evolution seen in other works with the results of our survey. It is also found that the overall properties of $[\text{OII}]$ kinematics at intermediate redshifts are varied. For example, 25% of the field galaxies in the sample have $[\text{OII}]$ kinematics unrelated to rotation; $[\text{OII}]$ emission is confined to the nucleus in most of these galaxies. Anomalous kinematics is found to be related to the presence of companions — i.e. minor merger events. A Doppler ellipse similar to those found in local dwarf galaxies has been observed in a $z = 0.35$ galaxy, and may be interpreted as a supernova-driven supershell.

Subject headings: galaxies: kinematics and dynamics — galaxies: evolution — methods: data analysis

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1. Introduction

The observed number counts of faint galaxies exceed the predictions of standard models in which evolutionary effects are ignored. Yet the faint galaxy redshift distribution appears to be well modelled by these same no-evolution models (Lilly et al. 1995, Lilly 1993, Koo and Kron 1992, and references therein). The amount of evolution that faint galaxies have undergone (relative to galaxies at the present epoch) is clearly a critical parameter for understanding the Universe at intermediate redshifts. Here we focus on the novel technique of internal kinematics for studying galaxy evolution.

Internal kinematics is directly related to a single fundamental property of galaxies: mass. Observations of the velocity field of intermediate redshift galaxies can therefore be used to quantify the amount of luminosity evolution that these galaxies have undergone. As an illustration, consider a galaxy with rest-frame absolute luminosity equal to that of the Milky Way. If this galaxy were also as massive as the Milky Way (i.e. if it were unevolved in luminosity relative to the Milky Way), then a rotation velocity of \( \sim 200 \text{ km/s} \) would be observed. On the other hand, if it were in fact a lower mass object that had been boosted in luminosity by \( \sim 10 \times \) (as suggested in the luminosity-dependent luminosity evolution scenario – Broadhurst et al. 1988), then the TF relation would predict a rotation velocity \( \sim 100 \text{ km/s} \).

This kinematical approach to measuring evolution is direct. It is not affected by uncertainties in models based on local luminosity functions. Furthermore, whereas luminosity functions derived from redshift surveys constrain the average amount of evolution in an entire galaxy population, the present approach can measure luminosity enhancement in individual galaxies, and can thus tie luminosity evolution directly to galaxy properties on a galaxy by galaxy basis.

Most previous kinematical studies (Franx 1993, Vogt et al. 1993, Colless 1994, Koo et al. 1995, Forbes et al. 1996) have suffered either from small sample size, or from a lack of spatial information; but they have clearly demonstrated that current telescopes are adequate to the challenge of measuring the internal kinematics of intermediate redshift galaxies. Recently, Vogt et al. (1996) presented a beautiful set of rotation curves (observed with the Keck Telescope) for nine faint field galaxies in the redshift range \( 0.1 \leq z \leq 1 \). These rotation curves appeared similar to those of local galaxies in both form and amplitude. The kinematics of the Keck galaxies showed evidence for only a modest increase in luminosity (\( \Delta M_B \leq 0.6 \text{ mag} \)) compared to the local Tully-Fisher relation. This is in apparent disagreement with the strong evolution in galactic disks observed by Schade et al. (1996) over the range \( 0.1 < z < 0.6 \).

In this paper, we present the internal kinematics of a sample of intermediate redshift galaxies, and demonstrate how luminosity-dependent luminosity evolution can reconcile observations of surface brightness and internal kinematics.

2. Observations

Twenty field galaxies and two cluster galaxies in the redshift range 0.25–0.45 were selected from the CNOC cluster survey database (Yee et al. 1996). This database contains position, Gunn r magnitude, \( g - r \) color, and redshift for thousands of galaxies. Elongated objects were preferentially selected to minimize \( \sin i \) effects. No size/color selection criteria were used. Rest-frame [OII] equivalent widths \( W_{3727} \) were chosen to lie between 20 and 50 \( \text{Å} \). Target galaxies may be [OII] strong relative to local early-type (Sb and earlier) spirals, but they have the same \( W_{3727} \) as many local late-type (Sc and later) galaxies (Kennicutt 1992). Our range of \( W_{3727} \) is also representative of the excess galaxy population at intermediate redshifts (Broadhurst et al. 1988, Broadhurst et al. 1992).

Spatially-resolved observations of the [O II] \( \lambda \lambda 3726.1, 3728.8 \text{ Å} \) doublet emission line were obtained with the Multi-Object Spectrograph (MOS) and the Subarcsecond Imaging Spectrograph (SIS) at the Canada-France-Hawaii 3.6-m Telescope (CFHT) in July-August 1994. SIS was ideally suited for studying [OII] kinematics because SIS “tip-tilt” corrections yielded a seeing FWHM of \( 0''.5 - 0''.6 \). We used the B600 grism and a LORAL 2048\times2048 CCD (QE = 23\%, \( N_R = 8 \text{ e}^- \)). The detector was binned by 2 along both axes to improve S/N ratio. Image scale and dispersion were \( 0''.31/\text{pixel} \) and 1.58 \( \text{Å/pixel} \) (MOS) and \( 0''.17/\text{pixel} \) and 0.88 \( \text{Å/pixel} \) (SIS). Typical total integration time per galaxy was 7200 seconds split in 2–3 exposures for cosmic ray removal.

3. Synthetic Rotation Curve Fitting

Flux levels in [O II] were very low (typical S/N ratio per pixel \( \sim 2–3 \)); it was therefore important
to choose a method of analysis which used all of the pixels simultaneously to statistically find the best parameter values and their respective uncertainties. We adopted a synthetic rotation curve fitting technique, in which models were compared to the two dimensional distribution of pixel intensities in the [O II] line (the two dimensions being wavelength or velocity, and position along the slit). The parameters of the fitting model were the projected rotation velocity $V_{rot}$ sin $i$ of the galaxian disk in km/s, the [OII] exponential disk scale length $r_d$ in h$^{-1}$ kpc, the [OII] total line flux in DU, and the dimensionless [OII] doublet intensity ratio $I(3726 \text{Å})/I(3729 \text{Å})$. (It was necessary to include this doublet intensity ratio in the model because the [O II] doublet is partially resolved due to $(1+z)$ spectral stretching.)

The 2D model distributions of pixel intensities were constructed assuming that the [OII] emission was distributed in a thin exponential disk with a flat rotation curve. These [OII] model disks were convolved with a point-spread-function (PSF) extracted from direct images; the effect of placing a slit in front of the image was then computed. Finally, the flux passing through the synthetic slit was convolved with the spectrograph instrumental line shape, which was extracted from comparison arc lines.

The best fitting parameter values were found using the Metropolis algorithm (Saha and Williams 1994). This Bayesian algorithm starts with some set of parameter values $\omega$ and the associated $P(\omega|D, M)$ — the probability that $\omega$ is the true parameter set given the data D and a model M. It then picks a possible change $\delta \omega$ in the parameters and computes $P(\omega + \delta \omega|D, M)$. If $P(\omega + \delta \omega|D, M) > P(\omega|D, M)$, then the change $\delta \omega$ is accepted. If $P(\omega + \delta \omega|D, M) < P(\omega|D, M)$, then the change $\delta \omega$ is accepted only some fraction $P(\omega + \delta \omega|D, M)/P(\omega|D, M)$ of the time. After hundreds of iterations, the distribution of accepted $\omega$ values will converge to $P(\omega|D, M)$ provided that all possible $\omega$ are eventually accessible. Parameter space is thus sampled with a density proportional to the likelihood.

The trial changes $\delta \omega$ are chosen at random. If they are too small (i.e. the parameter search is too “cold”), then all iterations will accept changes. If the search is too “hot”, then none of the iterations will accept changes. The “temperature” of the search is regulated so that half the iterations accept changes. As the algorithm proceeds, trial values are stored to simultaneously derive the best parameter values and their respective error distribution. For each parameter, we took the median value of $P(\omega|D, M)$ as the best value and the 16th and 84th percentile values as our “1 $\sigma$” error bars. We tested confidence intervals and parameter value recovery using a set of 342 simulated rotation curves. We chose input parameter values in these simulations to yield worse S/N ratios than seen in the data. No biases were detected. The Metropolis parameter estimates were also more robust to noise than least-squares estimates at low S/N ratios.

4. Results

4.1. [OII] Morphologies

[OII] kinematics at intermediate redshifts is varied. Seven galaxies have [O II] scale lengths significantly smaller than their broad-band scale lengths, consistent with central unresolved [O II] sources. Two of these “unresolved [O II]” galaxies are serendipitously observed cluster galaxies (we cut extra slitlets on the mask for cluster galaxies whenever possible). Such discrepancies indicate that the [OII] gas kinematics is decoupled from galaxy rotation in some galaxies and could be confined to the nucleus. Two properties of kinematically anomalous galaxies have emerged so far: (1) All but one have close companions. This suggests that enhanced star formation activity may be the result of merger events. (2) Some of these galaxies appear to be of early-type. Kinematically “anomalous” field galaxies make up 25% of the field sample. This is similar to the fraction of blue-nucleated galaxies observed in HST images of galaxies at $z \sim 0.6$ (Schade et al. 1995).

In one galaxy at $z = 0.35$, the [OII] line was donut-shaped. This line shape could be interpreted in two ways: either (1) the line is made of two rotation curves from two galaxies very close together, or (2) the line arises from an expanding supershell, presumably driven by supernova winds from a massive starburst. If option (2) is correct, then the supershell has a diameter of 2.5 h$^{-1}$ kpc and a rest-frame expansion velocity of about 80 km/s. These characteristics are amazingly similar to those of supershells observed in local dwarf irregular galaxies (Marlowe et al. 1995, Martin 1995). In another galaxy at $z = 0.42$, there is a relatively strong [OII] source unresolved both spectrally and spatially superimposed over a fainter rotational [O II] component. The source could be a giant HII region 2.6 h$^{-1}$ kpc from the center of the
4.2. An Intermediate Redshift Tully-Fisher Relation

Figure 4 shows kinematical evidence for luminosity evolution at intermediate redshifts. The locus of the local $H_\alpha$ rotation velocity–$B$ band Tully-Fisher (TF) relation for all morphological types (from the data of Mathewson et al. 1992) is used as a reference. Solid circles are the rest-frame $V_{\text{rot}} \sin i$’s versus rest-frame $B$ magnitude for the kinematically normal galaxies in our sample — i.e. galaxies with [OII] scale length consistent with their broad-band scale length. $B$-band k-corrections were computed using the tables of Frei and Gunn (1994). The upper long dashed line is an unweighted linear fit to all local morphological types. This linear fit was then shifted by $\Delta M_B = -1.0$ mag (middle dashed line) and $\Delta M_B = -2.0$ mag (lower dashed line) to represent various degrees of luminosity evolution.

Galaxies in our sample are $\sim 1.5–2.0$ magnitudes brighter than expected from their rotation velocity, given the local TF relation defined by the Mathewson et al. sample. Such a large local sample clearly shows the scatter in the local TF relation. Locally, there are no systematic shifts between loci of different morphological types, but it is obvious that certain types (e.g. $T = 6$) display larger dispersions.

5. Discussion

The scatter in the local TF relation has a direct impact on the exact amount of luminosity evolution derived from our observed TF relation at intermediate $z$. This is because scatter in the local TF relation may correlate with star formation rates, and hence emission line strengths. In order to accurately measure magnitude offsets relative to the local Tully-Fisher relation, each galaxy in our CFHT sample (or, for that matter, any other sample) should be compared to the local Tully-Fisher relation for galaxies with similar [OII] emission line strengths. This is not possible at present. A large, homogeneous sample of local emission-line strengths, rotation velocities, morphologies and absolute magnitudes is required to settle this issue. This will remain a major limitation of internal kinematics studies at high redshifts as long as technical requirements restrict such studies to strong emission-line objects.

The luminosity-dependent luminosity evolution scenario neatly reconciles the various amounts of luminosity evolution seen in the surface brightness and internal kinematics studies. At the low end of the galaxy mass spectrum, Koo et al. (1995) looked at compact, unresolved galaxies with narrow emission line widths. The line widths of these galaxies were $2–3 \times$ lower than expected from the TF relation of normal spiral galaxies, implying large amounts of evolution ($\sim 3$ mag). These low-mass galaxies had linewidths similar to those of local HII galaxies. At the high end of the galaxy mass spectrum, the Keck study of Vogt et al. (1996) selected galaxies that were intrinsically large ($r_d \geq 3.0$ kpc) and bright ($M_B \leq -20.7$). These galaxies were also intrinsically massive, with typical rotation velocities of $200 \text{ km/s}$. The increase in $B$ luminosity with respect to the local TF relation was less than 0.6 mag.

Our CFHT sample occupies a niche in size and mass between the above two Keck samples. The CFHT galaxies are typically a full magnitude fainter than the objects in the Vogt et al. study. They are also intrinsically smaller with typical disk scale lengths less than 2.0 kpc, and some of them are barely resolved. They are also less massive, with rotation velocities $\sim 100 \text{ km/s}$, but they are nonetheless more massive than the galaxies observed by Koo et al.. If mass is taken as an indicator of the luminosity that a galaxy would have had in a quiescent phase, then all three internal kinematics studies can be understood with luminosity-dependent luminosity evolution.

The $B$-band surface brightness $\mu_0(B)$ of field disk galaxies undergoes strong evolution over the redshift range $0.1 < z < 0.6$ compared to two different local log $r_d$–$M_{AB}(B)$ relations: the Freeman law and an empirical $z = 0.06$ relation for galaxies in Abell 2256 (Schade et al. 1996). At a redshift of 0.5, $\Delta \mu_0(B)$ is equal to $-1.1$ mag. This is consistent with or perhaps slightly less than the evolution seen in our CFHT sample, but it is certainly more than the amount of evolution seen in the Keck sample of Vogt et al.. Looking at Figure 1 of Schade et al., there is a hint that surface brightness evolution depends on disk scale length: smaller galaxies evolve more drastically than large galaxies. The effect is particularly noticeable in the highest redshift bin where the log $r_d$–$M_{AB}(B)$ relation clearly curves “down”. Taking $M_B \simeq -21$ and $<r_d> = 4.3$ kpc ($H_0 = 75$), one can see on the Schade diagram for $0.45 < z < 0.65$ that a number of bright, large galaxies at ($\log r_d = 0.8$, $M_{AB}(B) = -21$) show
little or no evolution – similar to what is observed in the Keck sample!

The diversity of [OIII] kinematics and the significant amount of luminosity evolution seen in our survey illustrate the power of internal kinematics as a probe of the nature of intermediate redshift galaxies. Although samples are small compared to those of redshift surveys, they already provide exciting direct evidence that luminosity-dependent luminosity evolution may indeed be at the root of the faint galaxy excess problem. Tying internal kinematics to other galaxy properties on a galaxy by galaxy basis will play a key role in our understanding of galaxy evolution at intermediate redshifts.

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Table 1
TARGET GALAXIES: CHARACTERISTICS AND RESULTS.

| ID          | z      | Gunn r | Gunn (g - r)_obs | W_{3727} (Å) | M_{B_0} | V_{rot} sin i (km/s) | r_d (h^{-1} kpc) |
|-------------|--------|--------|------------------|--------------|---------|---------------------|-----------------|
| A2390-101033^n | 0.2460 | 18.90  | 0.70             | 55           | -20.3   | -212 + 9 0.09       | +0.02 |
| A2390-100686^n | 0.3822 | 21.22  | 0.67             | 21           | -19.4   | 91 + 41 2.3 + 0.50  | -0.49 |
| A2390-350416^n | 0.2558 | 20.14  | 0.27             | 35           | -19.5   | 62 + 18 1.9 + 0.40  | -0.49 |
| A2390-350471^n | 0.2559 | 19.40  | 0.28             | 21           | -20.3   | 171 + 26 2.2 + 0.70  | -0.50 |
| E1512-301037^n | 0.3457 | 21.41  | 0.19             | 41           | -19.1   | 77 + 22 1.8 + 0.20  | -0.50 |
| E1512-301037^n | 0.3457 | 21.41  | 0.19             | 41           | -19.1   | 86 + 8 0.8 + 0.40   | -0.29 |
| E1512-101526^n | 0.4026 | 20.36  | 1.12             | 48           | -20.2   | -222 + 143 0.1 + 0.10 | +0.20 |
| E1512-20149^n  | 0.4231 | 20.44  | 0.56             | 26           | -20.4   | 151 + 13 1.0 + 0.20  | -0.10 |
| E1621-100515   | 0.3455 | 20.00  | 0.42             | 22           | -20.3   | -237 + 11 0.8 + 0.19  | -0.10 |
| A2390-100225   | 0.3829 | 21.65  | 0.89             | 26           | -18.9   | 61 + 121 0.6 + 0.59  | -0.49 |
| A2390-101084^n | 0.2302 | 17.31  | 0.68             | 110          | -21.7   | -271 + 12 0.4 + 0.03  | +0.06 |
| A2390-200928^n | 0.2645 | 21.51  | 0.22             | 40           | -18.2   | 65 + 13 0.3 + 0.20  | -0.10 |
| A2390-200802^n | 0.3208 | 21.16  | 0.37             | 25           | -19.1   | -198 + 65 1.0 + 0.40  | -0.50 |
| A2390-200372^n | 0.3485 | 20.15  | 0.65             | 16           | -20.2   | -86 + 52 3.2 + 0.90  | -0.60 |
| E1512-201845^n | 0.3387 | 19.60  | 0.82             | 36           | -20.5   | 385 + 18 0.4 + 0.10  | +0.10 |
| E1512-201773   | 0.3383 | 20.06  | 0.35             | 26           | -20.3   | -116 + 31 0.9 + 0.19  | -0.10 |
| E1512-200730^n | 0.4266 | 21.35  | 0.58             | 32           | -19.5   | -1 + 7 0.2 + 0.10   | -0.10 |
| E1512-200334^n | 0.4142 | 21.81  | 0.70             | 36           | -19.0   | 60 + 36 1.5 + 0.30  | -0.20 |
| E1512-200672^n | 0.4152 | 21.85  | 0.43             | 29           | -19.1   | 44 + 56 0.3 + 0.10  | -0.10 |
| E1512-201268^n | 0.3412 | 21.77  | 0.39             | 29           | -18.6   | 33 + 45 1.4 + 0.30  | +0.20 |
| E1512-202096^n | 0.4252 | 20.33  | 0.66             | 23           | -20.5   | 28 + 39 2.0 + 0.30  | -0.30 |
| E1512-201125^n | 0.3823 | 21.69  | 0.74             | 15           | -18.9   | 59 + 79 0.5 + 0.30  | -0.30 |

^nKinematically anomalous galaxy
^nKinematically normal galaxy
^nSerendipitously observed cluster galaxy

Note.—(1) Galaxy identification code. First part is the CNOC cluster name and the second part is the CNOC PPP number; (2) CNOC galaxy redshift; (3) CNOC observed Gunn r magnitude; (4) CNOC observed Gunn g - r color; (5) Rest-frame [OII] equivalent width. Obtained by dividing the observed width by (1+z). Error ~ 10%; (6) k-corrected absolute B-band magnitude (H_0 = 75 km s^{-1} Mpc^{-1}, q_0 = 0.5). Error = ±0.1 mag; (7) Rest-frame projected [OII] disk rotation velocity with 68% confidence interval; (8) [OII] exponential disk scale length with 68% confidence interval (h = H_0/(100 km s^{-1} Mpc^{-1}), q_0 = 0.5). Galaxies with no superscript were rejected because cosmic rays hit the [OII] line directly, or simulations showed that the [OII] flux was too low to derive reliable kinematical parameters.
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Fig. 1.— Kinematical evidence for luminosity evolution at intermediate redshifts. The locus of the local H$_\alpha$ rotation velocity–B band Tully-Fisher relation for all morphological types as defined by data taken from Mathewson et al. (1992) is used as a reference. Solid circles are the V$_{\text{rot} \sin i}$’s versus rest-frame B magnitude for the kinematically normal galaxies in our sample. The upper long dashed line is an unweighted linear fit to all the local morphological types. This linear fit was then shifted by $\Delta M_{B_0} = -1.0$ mag (middle dashed line) and $\Delta M_{B_0} = -2.0$ mag (lower dashed line) to represent various degrees of luminosity evolution.
\[ \log V_{\text{rot}} \text{ (km s}^{-1}\text{)} \]

\[ M_{B_0} - 5 \log h \]

- T1 (Sa)
- T3 (Sb)
- T4 (Sbc)
- T5 (Sc)
- T6 (Scd)
- T7 (Sd)
- T8 (Sdm)
- data