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HIGH-RESOLUTION SPECTRA OF DISTANT COMPACT NARROW EMISSION LINE GALAXIES: PROGENITORS OF SPHEROIDAL GALAXIES?[1,2]

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ABSTRACT

Emission-line velocity widths have been determined for 17 faint ($B \sim 20$–23) very blue, compact galaxies whose redshifts range from $z = 0.095$ to 0.66. The spectra have a resolution of 8 km s^{-1} and were taken with the HIRES echelle spectrograph of the Keck 10 m telescope. The galaxies are luminous with all but two within 1 mag of $M_B \sim -21$. Yet they exhibit narrow velocity widths between $\sigma = 28$–157 km s^{-1}, more consistent with typical values of extreme star-forming galaxies than with those of nearby spiral galaxies of similar luminosity. In particular, objects with $\sigma \leq 65$ km s^{-1} follow the same correlations between σ and both blue and Hβ luminosities as those of nearby H II galaxies. These results strengthen the identification of H II galaxies as their local counterparts. The blue colors and strong emission lines suggest these compact galaxies are undergoing a recent, strong burst of star formation. Like those which characterize some H II galaxies, this burst could be a nuclear star-forming event within a much larger, older stellar population. If the burst is instead a major episode in the total star-forming history, these distant galaxies could fade enough to match the low luminosities and surface brightnesses typical of nearby spheroidals like NGC 185 or NGC 205. Together with evidence for recent star formation, exponential light profiles, and subsolar metallicities, the postfading correlations beween luminosity and velocity width and between luminosity and surface brightness suggest that among the low-σ galaxies, we may be witnessing, in situ, the progenitors of today's spheroidal galaxies.

Subject headings: cosmology: observations — galaxies: compact — galaxies: evolution — galaxies: formation — galaxies: fundamental parameters

1. INTRODUCTION

The observational study of the formation and evolution of distant galaxies is at a watershed with the advent of two important optical telescopes. Measurements of size, shape, and morphology from the *Hubble Space Telescope* (*HST*) can be complemented by spectra of galaxies to $B \sim 24$ and fainter from the Keck 10 m Telescope. High signal-to-noise ratio (S/N), high-resolution Keck spectra provide three new, powerful diagnostics for the analysis of distant galaxies, namely internal velocities (and hence masses when size is used), abundances, and age estimates. These are some of the key parameters needed to relate the properties of local galaxies to those of galaxies in the early universe. Such an approach to the study of distant galaxies is the focus of a new initiative called the Deep Extragalactic Evolutionary Probe or DEEP (Mould 1993; Koo 1995). This *Letter* reports on the possible identification of the progenitors of today's spheroidal galaxies, based on new, high-resolution Keck spectra showing low velocity widths for a sample of distant, luminous, blue compact galaxies.

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[2] Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the California Institute of Technology and the University of California.

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2. OBSERVATIONS AND DATA REDUCTION

2.1. *Keck Spectroscopy*

Twelve of the primary targets for Keck observations were selected from a set of compact, narrow emission line galaxies (CNELGs) at $z \sim 0.1$–0.7, originally identified as stellar-like objects with colors unlike typical stars in *UBV* two-color diagrams (see Koo et al. 1994). We also observed five galaxies with very blue colors, known redshifts, and strong emission lines indistinguishable from those of CNELGs. They were, however, more extended than stars, with sizes about twice that of the CNELGs (except SA 57-16288), but still within the smallest quartile of the field galaxies.

Observations were taken on the moonless, clear, nights of UT 1994 May 10–11, with seeing around 1″ FWHM. We used the high-resolution echelle spectrograph (HIRES) designed and built at Lick Observatory by S. Vogt (Vogt et al. 1994). The slit width was 1″.15, yielding a final resolution of 8 km s^{-1} on the Tektronix 2048^2 CCD. The slit lengths were either 7″ or 14″. In all but two cases, the [O II] 3727 Å doublet was included at the blue end of our spectral range. Internal quartz lamps were used for flats; a Th-Ar arc lamp was used for wavelength calibration. All exposures were 1800 s, except for two galaxies which had slightly shorter exposures.

Even in their raw state, the HIRES images clearly showed [O II] 3727 Å resolved for most of the sample (see Fig. 1 [Pl. L3]), thus indicating that the velocity widths were well below the 220 km s^{-1} separation of the doublet. We note in

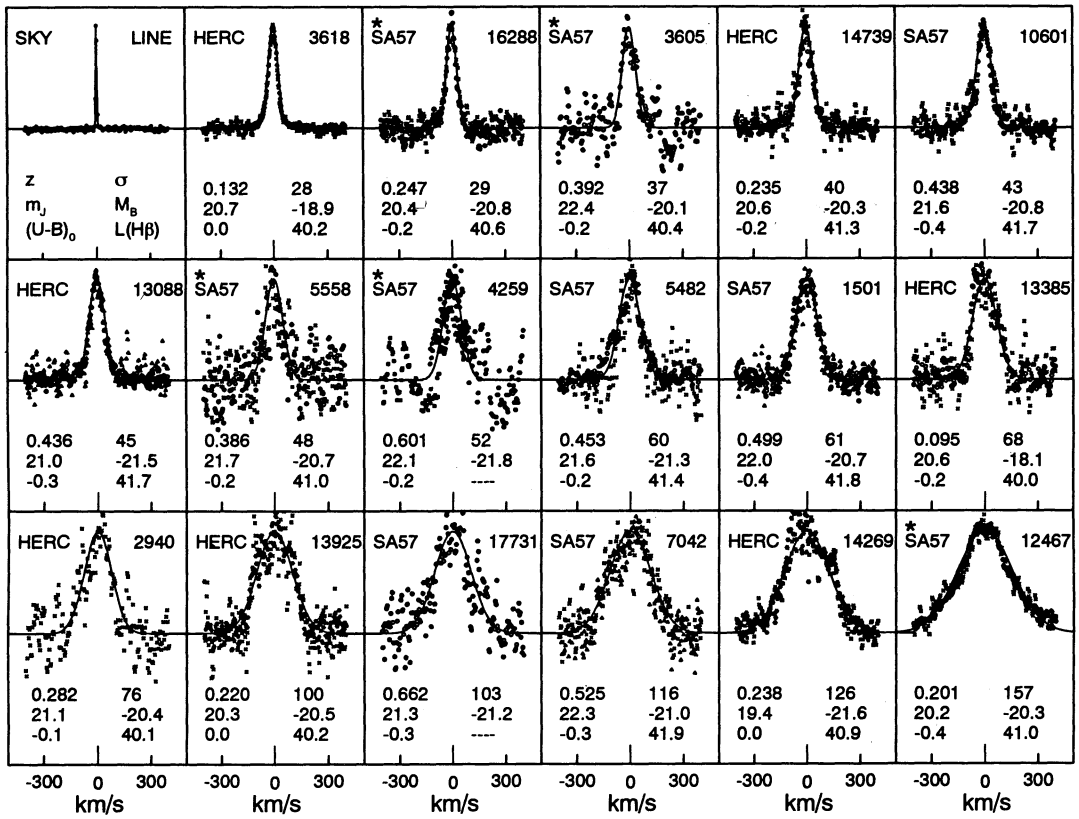

FIG. 2.—Panel of emission-line profiles in km s^{-1}, rather than wavelength, for all 17 galaxies. In the upper left-hand panel, a typical night-sky line shows our instrumental resolution of $\sigma = 3.4$ km s^{-1}. Each panel is labeled at the top with the ID name (field and number) and includes the redshift (z), velocity width in km s^{-1} (σ), apparent blue B_J magnitude (m_J), rest frame B absolute magnitude (M_B), rest frame $U-B$ color, and Hβ luminosity in logarithmic units of ergs s^{-1} [L(Hβ)], in positions as shown in the upper left-hand panel. Those ID fields with asterisks are very blue, fuzzy galaxies; the remainder are CNELGs. Solid lines show the best Gaussian curve that fits the average of profiles from all emission lines. Two different symbols denote spectral points for the two *strongest* emission lines for each object.

passing that, except for some nearby galaxies such as M81 (Munch 1959) and certain H II galaxies (Melnick, Terlevich, & Moles 1988), our HIRES targets are among the few galaxies ever observed at such high spectral resolution and are likely the faintest and highest redshft objects for which [O II] has been split.

Most spectra had good S/N for several emission lines ranging from [O II] 3727 Å to the [S II] lines around 6720 Å. A detailed study of the line profiles is beyond the scope of this *Letter*, but, unlike the case for most luminous spiral galaxies, the lines are found to be well fitted by Gaussians. We will thus characterize the lines by the rms velocity width (σ = FWHM/2.35 in km s^{-1}), as is commonly done for ellipticals.

Figure 2 shows the data points for the two strongest lines in each of the 17 targets as well as the Gaussian profile derived from the unweighted average of fits to several lines. From the variance among the different lines, we estimate that the average velocity widths are accurate to 4%–6%. Though most of the profiles have a roughly Gaussian shape, some are more complex with hints of asymmetry, multiple components, and, in the extended galaxy SA 57-16288, an apparent tilt suggestive of rotation (see Fig. 1). The CNELGs are not resolved enough to reveal rotation by line tilts.

2.2. *HST Imaging*

In a separate study (GO 3797), we have obtained prerefurbishment *HST* images of the seven brightest CNELGs among a total sample of ~35 objects (Koo et al. 1994).[5] Half-light diameters are measured to be 0″.5–0″.8 (2–4 kpc),[6] and half-light rest-frame B surface brightnesses are ~18–20 mag arcsec^{-2}. An additional CNELG, SA 68-6403,[7] has since been measured in a similar manner from *HST* images taken for another program (GTO 3685). Although only two of the eight CNELGs with *HST* measurements overlap the Keck CNELG sample (HERC-3618 and 13385), the *HST* sample is representative and will be used to define the surface brightness properties of CNELGs as a class.

3. RESULTS AND DISCUSSION

3.1. *The Nature of CNELGs*

Despite their small half-light diameters of 2–4 kpc, the *HST* CNELGs are quite luminous, ranging from $M_B = -18.1$ to -21.6. Based on evidence for high ionization from various emission line ratios, very blue colors, small sizes, and high luminosities, Koo et al. (1994) suggest that their local counter-

[5] Note that the surface brightnesses in Table 2 of Koo et al. (1994) are incorrect and should be brighter by 1.505 mag.

[6] This *Letter* adopts a deceleration parameter of $q_0 = 0.1$, a Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1}, and a cosmological constant of $\Lambda = 0$.

[7] The object is at $z = 0.47$ and has an apparent $B = 22.03$ or $M_B = -21.18$, a rest-frame $U-B = -0.13$, and a measured half-light diameter of 0″.45 (3.4 kpc), which yields a rest-frame half-light B surface brightness of 17.80 mag arcsec^{-2}. Like the other seven CNELGs observed with *HST* (see Koo et al. 1994), its light profile ($D_1/D_{1/2} = 1.33$) is consistent with an exponential disk rather than with an $r^{1/4}$ law.

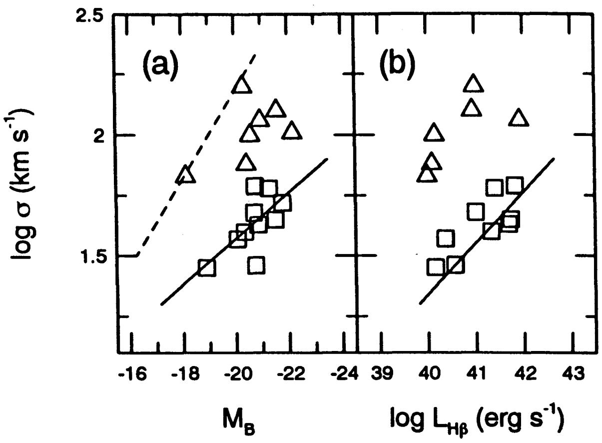

FIG. 3.—(*a*) Rest-frame *B* absolute magnitude (M_B) vs. velocity width σ in km s^{-1}. Squares are for six CNELGs and four fuzzier galaxies with $\sigma < 65$ km s^{-1}; triangles include six CNELGs and one fuzzy galaxy with $\sigma > 65$ km s^{-1}. The solid line shows the average relation derived for H II galaxies (Telles & Terlevich 1993) superposed on our data points. The dashed line shows the average relation for nearby spiral galaxies (Fouqué et al. 1990). (*b*) Hβ luminosity vs. σ in km s^{-1}. Symbols are as in (*a*). The solid line shows the average relation derived for H II galaxies by Melnick, Terlevich, & Moles (1988).

parts are not blue compact dwarfs, clumpy irregulars, or starbursts (Huchra 1987). Instead the distant CNELGs most resemble the more luminous, compact H II galaxies studied by French (1980) or Salzer, MacAlpine, & Boroson (1989).

With the Keck data, we are now in a position to explore further the nature of these compact galaxies via the relationship between velocity widths and both blue and Hβ luminosities[8] (Figs. 3*a* and 3*b*). A number of interesting points can be made. First, the σ range at a given luminosity is large, i.e., ~ 5 times. Second, we observe compact blue galaxies which fall in a continuum between the characteristic relations for normal spirals (Fouqué et al. 1990) and H II galaxies (see Telles & Terlevich 1993 and references therein). Third, many in the sample (those with $\sigma \leq 65$ km s^{-1}) follow remarkably well the trends found for local H II galaxies. Whether the galaxies with larger σ belong to a separate group is unclear, since the *local* H II galaxy sample includes only two such objects. The main point is that the velocity widths of compact, blue galaxies, at least for those with σ below 65 km s^{-1}, strengthen the association of CNELGs with the H II galaxy class.

3.2. *Formation of Spheroidal Galaxies?*

Most of our CNELGs are so blue (rest-frame $B-V \lesssim 0.4$) and have such strong emission lines [EW(Hβ) $\gtrsim$ 10 Å), that they are most likely to be near the peak of their luminosity after a strong burst of star formation. Unless reignited by new star formation, they should fade within a few Gyr. We use the models of Charlot & Bruzual (1991) to estimate the amount of fading 2–3 Gyr after a short burst. In this simple analysis, no corrections for metallicity, dust, gas emission, or possible previous and subsequent star formation, other than a single burst, are considered. For a Salpeter IMF, we derive that the fading in absolute blue magnitude is $\Delta M_B \simeq -5.7(U-B) + 4.3$, or typically 4–7 mag for our sample. Figure 4*a* shows the result of fading in M_B versus σ for the Keck sample; Figure 4*b* shows the result in M_B versus surface brightness (SB_e) for the eight *HST* CNELGs.

The final faded positions correspond to galaxies with low luminosity (i.e., $M_B \gtrsim -17$) and low surface brightness (i.e., $SB_e \gtrsim 23$). Nearby galaxies with red colors, small sizes, low velocity widths, and such faint luminosities and surface brightnesses comprise the spheroidal sequence (sometimes referred to as dwarf ellipticals; cf. Kormendy & Bender 1994). Indeed, as long as the observed burst creates a significant fraction (30% or more) of the distant galaxy's present-day stars, the descendants of our low-σ, distant galaxies are predicted to follow the same σ-M_B and SB_e-M_B relations as determined for nearby spheroidal galaxies (Bender, Burstein, & Faber 1992; Binggeli & Cameron 1991) (see Figs. 4*a* and 4*b*). Note how well the faded points in Figure 4*b* coincide with the Virgo spheroidal distribution, in particular the trend of increasing surface brightness with luminosity (Wirth & Gallagher 1984).

This simple scenario, however, appears in Fig. 4*a* to overestimate the fading for galaxies with $\sigma > 65$ km s^{-1}. This division by velocity width remains uncertain with our small sample but is suggestive of the demarcation below which supernovae-driven winds might play an important role in the formation of spheroidals (Dekel & Silk 1986). Galaxies with larger σ are expected to have quite different histories and properties. They may, e.g., possess a highly visible, starbursting gaseous disk in the nucleus and a near-invisible, underlying, extended old population of stars. Such galaxies are similar to some H II galaxies found locally (Salzer et al. 1989) and may provide an alternative explanation of the CNELGs, even those with low velocity widths. New *HST* and near-infrared data are needed to place improved constraints on the significance of such components for our CNELGs.

Other lines of evidence do support the speculation that some descendants of the distant, low-σ CNELGs might indeed be

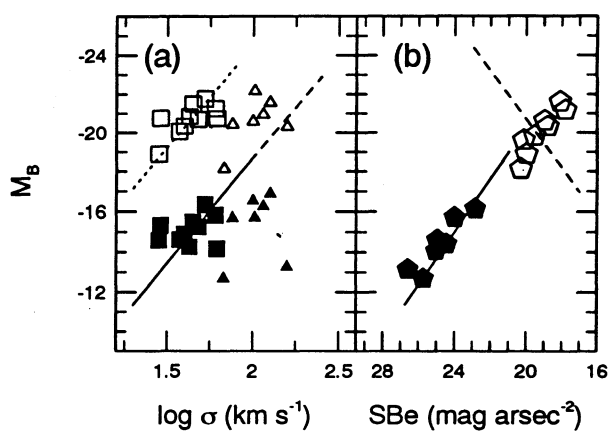

FIG. 4.—(*a*) Rest-frame *B* absolute magnitude (M_B) vs. velocity width σ in km s^{-1}. Open symbols are as in Fig. 3*a*. Solid symbols show the positions after fading by $5.7(U-B) + 4.3$ mag. The $U-B$ color is in the rest frame and galaxies are assumed to have undergone a short, dust-free single burst of star formation. The lines show the average relation (Faber-Jackson) derived for a sample of nearby spheroidal systems (*solid line*) and elliptical galaxies (*dashed line*) (Bender et al. 1992) and the relation derived for H II galaxies (*dotted line*) (Telles & Terlevich 1993). (*b*) Rest-frame *B* absolute magnitude (M_B) vs. the average rest-frame blue surface brightness within the half-light radius, *SBe* (mag arcsec^{-2}). Symbols apply to the eight CNELGs for which we have *HST* images (the faintest two are also in our Keck sample); open symbols are as observed while solid ones are after fading. The solid line is the average relation derived for a large sample of spheroidal systems in the Virgo Cluster (Binggeli & Cameron 1991). The dashed line represents the average relation for elliptical galaxies (Bender et al. 1992).

[8] The Hβ luminosities were calculated from the rest-frame equivalent widths of Hβ as measured from KPNO spectra and from rest-frame M_B based on KPNO 4 m plate photometry.

spheroidal galaxies of today. The light profiles of the eight *HST* CNELGs are more consistent with the exponential profiles of spheroidals than the $r^{1/4}$ profiles of giant ellipticals (Faber & Lin 1983; Wirth & Gallagher 1984). The rather recent (few Gyr) epochs for major bursts of star formation in Local Group spheroidals (Freedman 1992) are consistent with the lookback times corresponding to the redshifts of our distant CNELGs. Moreover, the subsolar metallicities of spheroidals (Peterson & Caldwell 1993) are in rough agreement with those of our CNELGs (i.e., O/H $\sim$ 0.5–0.8 solar).

We caution the reader that the issue of fading and transformation of one galaxy class to another is complicated, with many subtleties beyond the scope of this *Letter*. In particular, we note that the metallicity of CNELGs, though subsolar, is definitely high enough to indicate significant and earlier star formation that has not been considered in our simple fading analysis. The literature is rich with discussions of this and other issues. For example, Huchra (1977) provides an early discussion of the problems associated with the descendents of very blue galaxies; the appendix of Koo (1985) emphasizes the difficulty of defining and modeling the statistical evolution of very blue, fading populations; Babul & Rees (1992) discuss the effects of environment on formation of dwarfs; and Terlevich (1994) considers gradual mass, size, and velocity width changes in such galaxies. Although the real situation is more complex than we have portrayed here, we find no compelling arguments to discard the possibility that the starbursts of our luminous, low-σ CNELGs are dominant star-forming events in their history, so that some CNELGs are possible progenitors of today's spheroidal galaxies.

4. SUMMARY

The key result of our Keck observations is that a sample of very blue, luminous, compact galaxies at intermediate redshifts ($z \sim 0.1$–0.7) yields low internal velocities ($\sigma \sim 28$–157 km s^{-1}). The new data strengthen the identification of H II galaxies as local counterparts of the distant galaxies. With very blue colors and strong emission lines, the distant galaxies are likely to be undergoing a strong burst of star formation. The amount of older stars and thus actual fading needs to be checked, but we speculate that the observed bursts are dominant star formation episodes among the low-σ galaxies that will be followed by several magnitudes of fading. If so, the low-σ galaxies will then possess the surface brightnesses and velocity widths that characterize nearby spheroidals, the origin of which has been highlighted as an important mystery by Kormendy & Bender (1994). Thus some of these distant galaxies can be the progenitors of contemporary spheroidal galaxies. Since we find blue, compact, luminous galaxies over a wide range of redshifts, the inference is that such major star-forming episodes occurred in spheroidals over many Gyr, rather than at a single epoch at high redshifts $z \gtrsim 1$.

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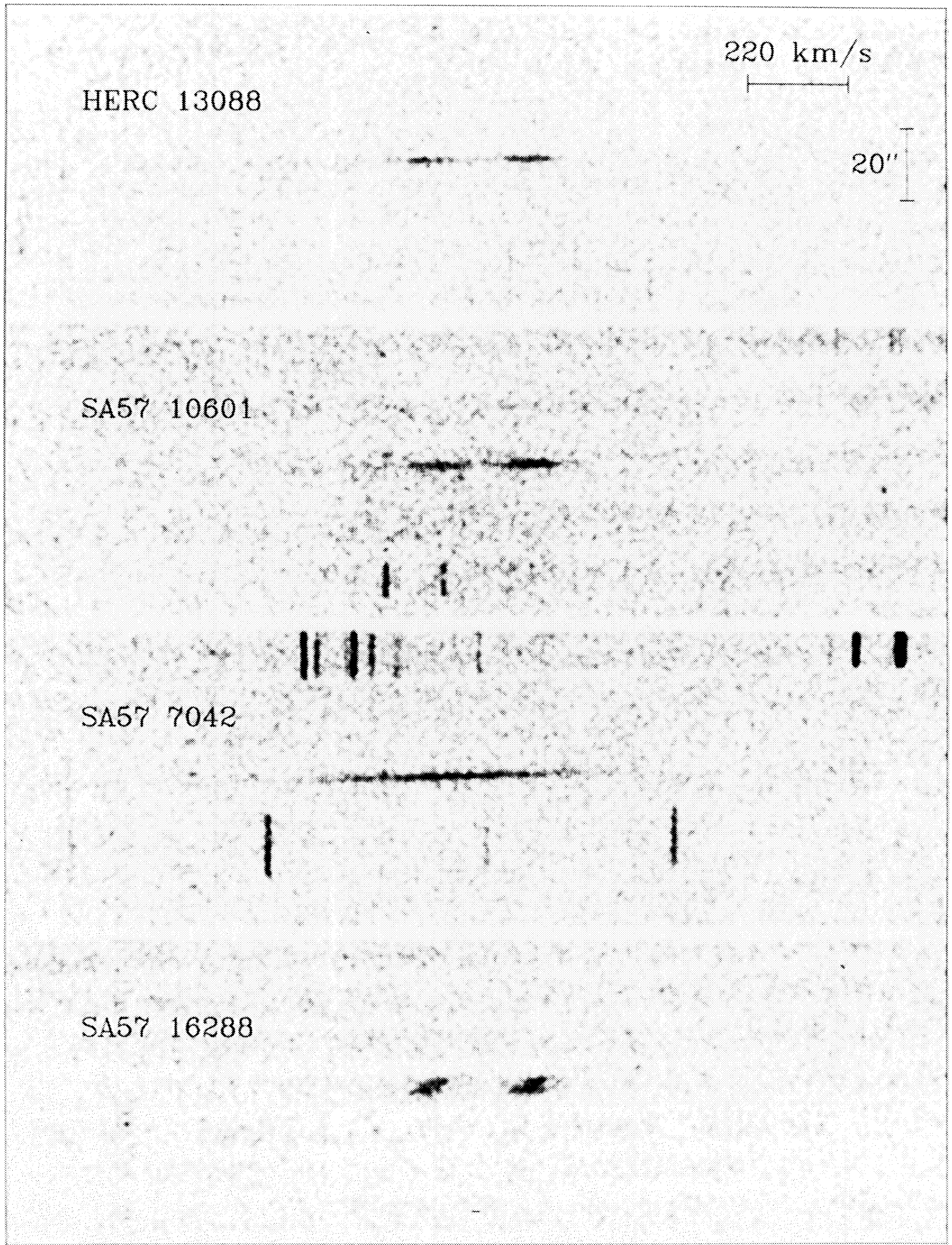

FIG. 1.—Examples of the reduced, but not yet sky-subtracted, two-dimensional images of [O II] observed with HIRES. The [O II] 3726.05 Å line is on the left and [O II] 3728.80 Å on the right. From top to bottom are galaxies: HERC-13088, SA57-10601, SA57-7042, and SA57-16288. Each image is 500 pixels wide, corresponding to 2000 km s^{-1} and 170 pixels high, corresponding to ~65″ along the slit. The narrow vertical segments are night-sky lines. Note the apparent tilt of the lines in SA57-16288.

KOO et al. (see 440, L49)