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UGC 12591: THE MOST RAPIDLY ROTATING DISK GALAXY

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ABSTRACT

Observations at 21 cm and optical observations of the S0/Sa galaxy UGC 12591 show that this galaxy possesses the largest rotational velocity of any disk system known so far. At 500 km s^{-1}, it exceeds by $\sim$ 30% the largest values previously measured. The 21 cm profile probably also exhibits an absorption feature near the systemic velocity of the galaxy. It is not yet certain whether UGC 12591 is a unique object at the extremum of the distribution, or one of a class of very massive, early-type disk galaxies, yet unrecognized because of instrumental limitations.

Subject headings: galaxies: internal motions — radio sources: 21 cm radiation

I. INTRODUCTION

The observation that most spiral rotation curves remain flat at large distances provides perhaps the most definitive evidence that the surface mass density of the gravitating system falls off no more rapidly than $1/r$. In a recent series of papers (Rubin, Ford, and Thonnard 1980; Rubin *et al.* 1982; Rubin *et al.* 1985), the forms of rotation curves for galaxies of different morphologies have been shown to be markedly similar.

While the similarity of the form of the rotation curve occurs between systems with diverse optical morphology, from large-bulged Sa's to small-bulged Sc's, the likeness does not extend to the amplitude of the rotation curve. Rubin *et al.* (1985) found that at a fixed luminosity, the maximum rotation velocities of Sa galaxies are about 1.6 times those of Sc galaxies. The dependence of maximum rotational velocity on type has been previously discussed by Brosche (1971) (although he did not separate by luminosity) and by Roberts (1978).

The width W of the global 21 cm line emission profile of a spiral galxy provides a good estimate of the maximum rotational velocity reached within the luminous disk. As found by Tully and Fisher (1977), when corrected to edge-on viewing, the 21 cm line width W_0 is itself an indicator of intrinsic luminosity. The slope of the magnitude-width relation is $\sim$ 10, although different morphological classes are offset from one another; the offset between the relations for Sa's and Sc's is about 2 mag in blue light (Rubin *et al.* 1985).

In his discussion of the 21 cm line widths, Roberts (1978) points out two potential biases. First, a strong Malmquist bias exists in the form of a correlation between intrinsic line width and distance. Roberts further notes the bias against the detection of very large width H I profiles imposed by current restrictions on the bandwidths of available 21 cm spectrometers. For a fixed H I mass, the peak intensity of the neutral hydrogen emission will decrease as the profile broadens. Thus, an Sa galaxy will show a peak 21 cm intensity 1.6 times lower than that of an Sc galaxy containing the same H I mass. Current instrumental limitations on both sensitivity and bandwidth have rendered the detection of very broad ($W \gtrsim 500$ km s^{-1}) and weak ($S_{\rm peak} \lesssim 5$ mJy) H I line signals very difficult. Roberts wondered whether galaxies with very large W may have been missed in many detection surveys. Because of the dependence of width on morphological type, this bias would be most severe among early-type spirals.

The development of new high-sensitivity receivers with both broader and intrinsically flatter spectral response is lifting the former restrictions, although the task of detecting broad, weak signals is an arduous one. Knapp and Gunn (1982) investigated the potential of obtaining H I spectra with a bandwidth of 40 MHz using the NRAO 43 m telescope; they obtained only flat, signal-free spectra, although with relatively modest sensitivity limits.

In Roberts's sample of almost 500 galaxies, none had an observed velocity width greater than 600 km s^{-1}, and only about eight had widths greater than 500 km s^{-1}. In the same study, widths corrected for inclination (for $i > 30°$) approach 700 km s^{-1}. He noticed that the relation between redshift and W showed a flattening for the very largest values of W and suggested that the intrinsic velocity width might continue to grow to values greater than 700 km s^{-1}. In this *Letter*, we report 21 cm and optical spectra of the S0/Sa galaxy UGC 12591. This galaxy has an observed velocity width of 1000 km s^{-1} and is the most rapidly rotating disk known.

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II. OBSERVATIONAL DATA

Located in the westernmost region of the Pisces-Perseus Supercluster, UGC 12591 is a 14th mag S0/Sa galaxy composed of a bulge partially obscured by prominent absorption arising from a disk. A summary of its relevant properties is given in Table 1. Because of its location, UGC 12591 was included in the 21 cm line survey of the Pisces-Perseus region undertaken by Giovanelli and Haynes (1985) with the Arecibo 305 m telescope. Because a feature (later found to coincide with one of the horns of the 21 cm profile) appeared to be detected 500 km s^{-1} off the already measured heliocentric optical redshift of 6935 km s^{-1} (Huchra *et al.* 1983), the galaxy was observed for more than the normal amount of observing time and with excellent baseline quality. The total integration time on source was 450 minutes, with an equivalent amount of time spent on a blank region of the sky. The instrumental configuration was the same as used in the general survey described by Giovanelli and Haynes; the Arecibo 21 cm dual circular feed system is discussed by Haynes and Giovanelli (1984, hereafter HG). The resultant accumulated and average spectrum of UGC 12591 is shown in Figure 1.

TABLE 1

RELEVANT PARAMETERS OF UGC 12591

Parameter	Value
Right ascension (1950)	$23^h22^m52^s.7$
Declination (1950)	28°13′22″
Type	S0/Sa
m_B	14.0
Size (UGC)	1′.6 × 0′.7
Inclination	67°
P.A. (major axis)	58°
V_0 (systemic, optical)	6915 ± 15 km s^{-1}
V_0 (systemic, radio)	6940 ± 10 km s^{-1}
Corrected H I flux integral	2.2 ± 0.4 Jy km s^{-1}
21 cm line widths:	
W_1 (at 50% of mean flux)	979 ± 11 km s^{-1}
W_2 (at 50% of peak flux)	950 ± 10 km s^{-1}
W_2 (corrected)[a]	1014 ± 10 km s^{-1}
Optical maximum observed velocity width	951 ± 11 km s^{-1}
Maximum rotational velocity (corrected)[a]	506 ± 6 km s^{-1}
H I mass[b]	1.1×10^{10} $M_\odot$
Blue luminosity[b] (1 mag extinction)	2.1×10^{11} $L_\odot$
Total mass within R_{25}[b]	1.9×10^{12} $M_\odot$

[a] Corrected for inclination and relativistic Doppler effect.
[b] Adopted H_0 = 50 km s^{-1} Mpc^{-1}.

The first unusual aspect of the spectrum of UGC 12591 is its width W, measured to be 979 km s^{-1} at a level of 50% of the mean intensity across the profile. To our knowledge, this is the broadest 21 cm width confirmed to arise from a single galaxy known to date. In addition, evidence is seen for absorption of the 21 cm radiation against the central source, estimated by current measurements to be about 126 mJy, a significant radio source at a redshift of nearly 7000 km s^{-1}. Continuum emission and optical appearance suggest some similarity to objects such as NGC 5363 and NGC 5128. Further investigation of the nature of the source and the absorbing clouds will require future higher resolution observations.

Except for its width, the form of the 21 cm profile in Figure 1 is not distinctive; it shows the characteristic two-horned signature of a rotating disk. Figure 2 (Plate L5) presents an enlargement of the Palomar Sky Survey blue print of the galaxy. A prominent dust lane is evident which is probably responsible for extinction in excess of one blue magnitude. That the extinction correction may be that large is corroborated by the observation that, in a diameter-magnitude diagram, UGC 12591 appears underluminous by 1–2 mag if an internal extinction correction is not applied. The disk appears to be inclined, but not perfectly edge-on, so that the width

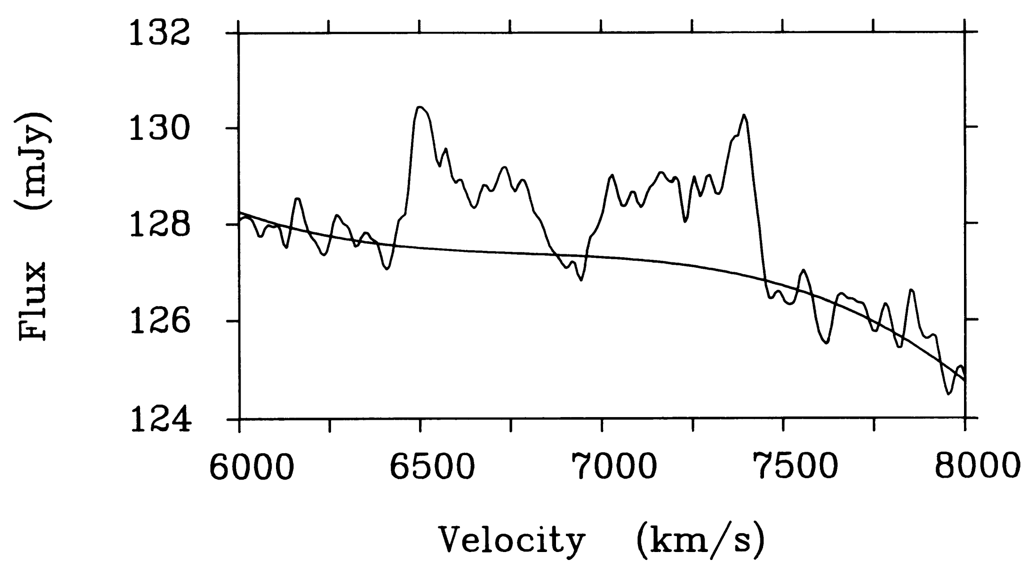

FIG. 1.—21 cm line profile of UGC 12591. The profile is smoothed to an effective resolution of 25 km s^{-1}. The offset of 126 mJy of the baseline level is due to the continuous emission of the galaxy itself. The rms error on this continuum flux is estimated at ~ 5%. The smooth line superposed on the profile represents the polynomial baseline subtracted before line parameters were measured. The dip in the profile near the systemic velocity is thought to arise from absorption of the nuclear continuum by disk gas.

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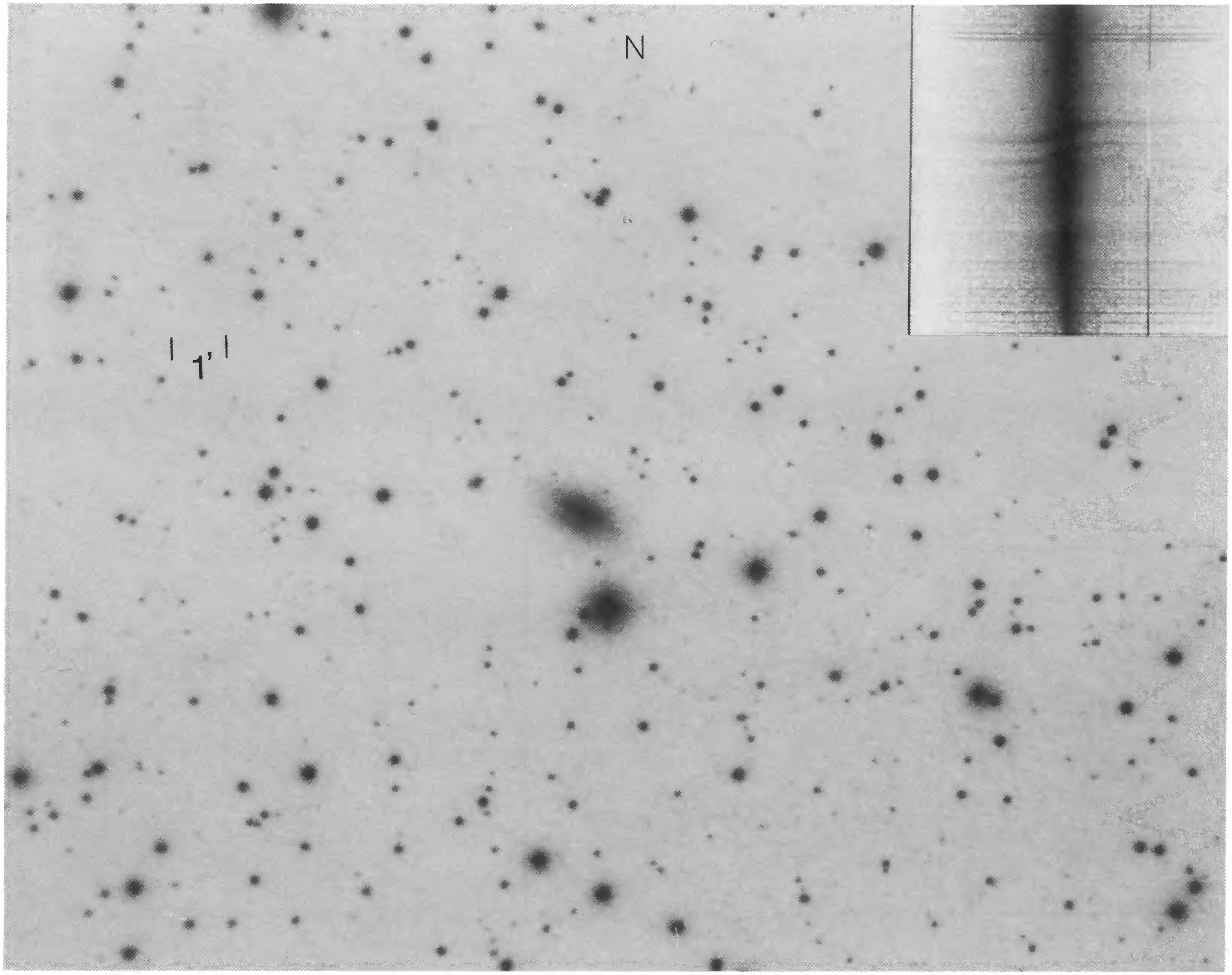

FIG. 2.—Enlargement of the Palomar Sky Survey blue print centered on UGC 12591. The UGC major and minor diameters are 1'.6 and 0'.7. *Insert*: Spectrum of UGC 12591, showing weak emission of Hα bracketed by [N II] lines, Palomar 200 inch CCD frame, taken with the slit in P.A = 238° along the major axis. Original scale and dispersion 0".59 pixel^{-1} and 0.8 Å pixel^{-1}, exposure 90 minutes.

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corrected for inclination is higher than the observed. An estimate for the inclination derived from the axial ratio following HG is 67°, giving a corrected profile width (at 50% of the peak) corrected for inclination and relativistic effects of 1014 km s^{-1}.

Also following HG, we derive the H I mass detected in UGC 12591, after correction for resolution and an estimated 35% for H I self-absorption, to be 1.1×10^{10} $M_{\odot}$ (for $H_0 = 50$ km s^{-1} Mpc^{-1}), a quite respectable amount of neutral hydrogen for a galaxy of type S0/Sa. With a peak intensity in the 21 cm line of only ~ 3 mJy, the H I in this galaxy would have eluded many of the previous surveys looking for neutral hydrogen in early-type spirals, despite its significant H I mass.

The half-power beam width of the Arecibo dual-circular feed system at 21 cm is about 3'.3. Because of the relatively large area subtended by the beam, it is always possible that nature might conspire to place more than one hydrogen disk within the beam, one hidden to optical inspection by projection behind the other. A previous report of an extraordinarily wide H I profile (Bothun *et al.* 1982*a*) in fact was subsequently shown likely to consist of two separate components (Bothun *et al.* 1982*b*).

In order to determine whether the spectrum illustrated in Figure 1 did indeed represent the rotation signature of a single galactic disk, a single high-resolution optical spectrum was obtained along the major axis with the slit in P.A. = 238° with the Palomar double spectrograph at the 200 inch (5.1 m) Hale telescope in 1984 October. The spectrum is shown inset within Figure 2. The frames were bias-corrected and flat-fielded in the conventional manner. At the CCD, one pixel equals 0''.59 along the slit and 0.8 Å along the dispersion.

Figure 3 shows the radial variation in the velocities projected to the plane of the galaxy and corrected for the relativistic Doppler effect (Harrison 1974). The form of the rotation curve is unexceptional. The rapid rise of velocities followed by a slight decline resembles the behavior seen in NGC 4378 (Rubin *et al.* 1985), a high-luminosity Sa galaxy. It is noteworthy that the four early-type spirals with large bulges, minimal disks, and highest rotational velocities, UGC 12591 (V_{max} = 506 km s^{-1}), NGC 669 (363 km s^{-1}; Rubin and Ford 1986), IC 724 (374 km s^{-1}), and NGC 4594 (367 km s^{-1}; Rubin *et al.* 1985) have rotation curves whose forms are very different. This lack of correlation of morphology and rotation curve form has been stressed by Burstein and Rubin (1985).

UGC 12591 is a weak emission-line object. The only lines visible between 6400 and 7000 Å were Hα and [N II]. [N II] λ6583 is everywhere more intense than Hα. We are aware of no other galaxy in which this is so. In NGC 669 (Rubin and Ford 1986) and NGC 4594 (Schweizer 1978), [N II] is generally stronger than Hα except for one or two regions at large nuclear distances. It is likely that the Hα emission is depressed by the presence of an underlying Hα absorption in the integrated bulge plus disk composite spectrum; greater spectral coverage is needed to identify accurately the stellar mix and to map the absorption properties. As the strength of the [N II] emission decreases with distance from the galaxy's center, it mimics fairly closely the decrease in surface brightness of the red continuum. Rubin and Ford are presently studying the implications of this similarity on the understanding of chemical variations across the galaxy.

In UGC 12591, the emission lines are also wide. Near the nucleus, Hα and [N II] lines have FWHM widths of almost 8 Å, or 350 km s^{-1}, and FWZI almost twice this value. We do not know how rare such broad lines are. Digital subtraction of the galaxy continuum has made it possible to view the bulge region emission lines which, for galaxies studied earlier, had been lost in the high-density red stellar continuum recorded on the photographic plate. With the bulge removed, the emis-

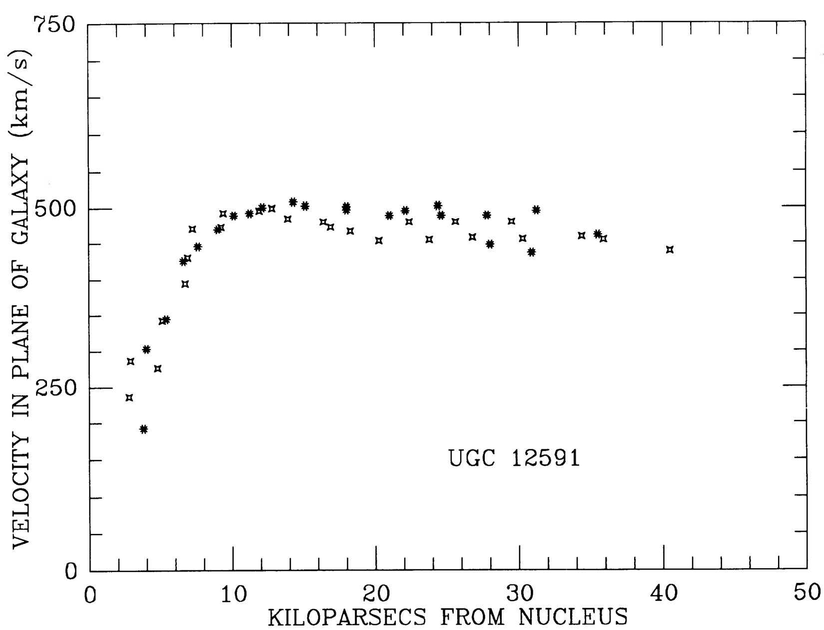

FIG. 3.—Optical rotation curve of UGC 12591, taken with the 200 inch Hale telescope. Each point represents an individual measurement either in the Hα or [N II] line emission; asterisks refer to the southwest side of the major axis, while stars identify points along the northeast side. Radial distance in kpc is calculated using H_0 = 50 km s^{-1} Mpc^{-1}, and velocities are projected to the plane of the disk and corrected for the relativistic Doppler effect.

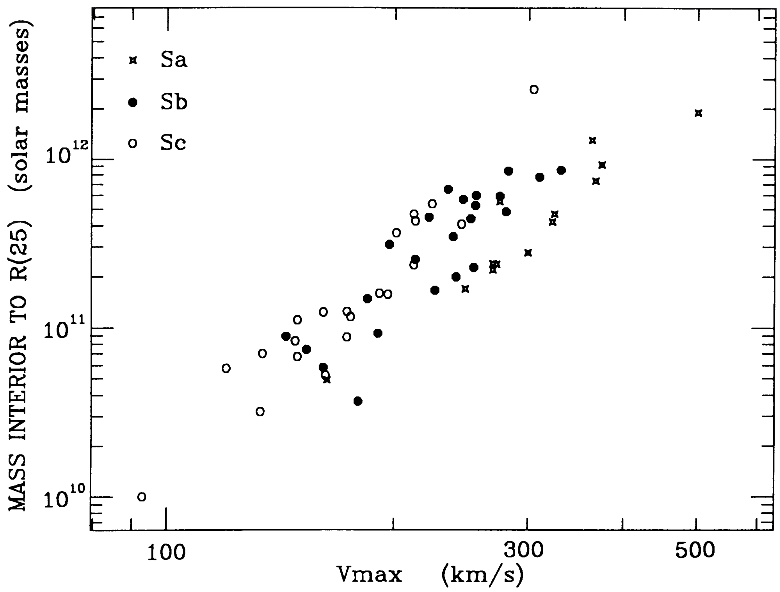

FIG. 4.—The correlation of mass interior to R_{25} vs. $V_{\max}$ for Sa, Sb, and Sc galaxies from Rubin *et al.* (1985), plus NGC 669 and UGC 12591. The two galaxies of highest mass are UGC 2885 (Sc) and UGC 12591 (S0/Sa).

sion lines appear to be almost discontinuous, where slower rotating nuclear gas merges into the disk. With spectra in one position angle only, we cannot tell if the nuclear gas is itself in a disk which is not coplanar with the prominent disk.

Prior to these observations, the highest published values of rotational velocities from optical observations were 374 km s^{-1} for IC 724 (Rubin *et al.* 1985), and the broadest 21 cm line width that of NGC 669, reported as 873 km s^{-1} (Giovanelli, Haynes, and Chincarini 1982). A more accurate estimate of the maximum rotational velocity of NGC 669 by optical means (Rubin and Ford 1986) gives a value of 363 km s^{-1}. UGC 12591, with $V_{\max} \approx 500$ km s^{-1}, has a rotational velocity which exceeds these previous values by over 30%.

III. CONCLUSIONS

In this *Letter*, we have reported the discovery of a spiral disk with a maximum rotational velocity in excess of 500 km s^{-1}. The dynamical mass interior to the isophotal radius R_{25} is high: 1.9×10^{12} $M_{\odot}$. Along with the Sc galaxy UGC 2885 [$V_{\max} = 304$ km s^{-1}, $R_{25} > 100$ kpc, $M(R_{25}) > 2 \times 10^{12}$ $M_{\odot}$; Burstein *et al.* 1982] its mass lies at the upper limit of masses known for spiral galaxies. The distribution of mass versus $V_{\max}$ for all Rubin *et al.* galaxies is shown in Figure 4. Even with $V_{\max} = 506$ km s^{-1}, UGC 12591 does not distort the correlation. Rather, it appears that spiral masses do not grow without bound: there is an upper limit to the amount of mass, luminous plus nonluminous, within an optical galaxy. Accurate values of M/L_B within R_{25} depend critically on the internal extinction within the galaxy, an amount which may be very large in UGC 12591 because of the broad obscuring lane visible in Figure 2. Reasonable guesses for the extinction produce values of $M(R_{25})/L_B$ on the order of 3–9, within the normal range for Sa galaxies.

UGC 12591 is a rather unobtrusive galaxy at first glance. In a normal H I survey conducted with a 10 MHz instantaneous bandwidth (about 2000 km s^{-1}), the width of its profile would have heavily conspired against detection, in spite of its relatively normal H I content. The detection reported here is definitely not a routine event. We cannot yet be certain how unique an object is UGC 12591, or whether it is only one of a class of supermassive early-type galaxies, yet unrecognized because of the practical limitations of current 21 cm spectrometers: the unique combination of the Arecibo 305 m telescope sensitivity and the new broad-band autocorrelation spectrometer to start operation in 1985 autumn will provide an answer.

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