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A NEW LOCAL GROUP GALAXY IN CETUS[1]

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ABSTRACT

We report the discovery of a previously uncataloged Local Group galaxy in the constellation Cetus. Faintly visible on UKST survey plates, it has a smooth, diffuse appearance and appears to be a dwarf spheroidal of type dE3.5. A color-magnitude diagram in V, $V-I$ shows a clear giant branch but no sign of recent star formation. From the position of the tip of the giant branch, we derive a reddening-corrected distance modulus of 24.45 ± 0.15 and a metallicity of -1.9 ± 0.2. With an implied heliocentric distance of 775 ± 50 kpc, and a corresponding Local Group barycentric distance of 615 kpc, the Cetus dwarf lies well within the boundaries of the Local Group, and although it currently lacks a radial velocity measurement, it is undoubtedly a member of the Local Group. The nearest Local Group galaxies are WLM and IC 1613 at angular separations of 7°.3 and 16°.3 and roughly 175 and 230 kpc total distance, respectively. Although the Cetus dwarf is unlikely to be directly associated with any other Local Group galaxy, it does lie in the general direction of the extension of the Local Group toward the Sculptor Group.

Key words: galaxies: distances and redshifts — galaxies: dwarf — Local Group

1. INTRODUCTION: DWARF GALAXIES AND DWARF HUNTING

The observational universe is built mostly from galaxies. For obvious reasons, most of the known (detected and cataloged) galaxies are intrinsically the largest and brightest ones, those that can be seen from the greatest distance and are most easily studied. Dwarf galaxies, however, dominate numerically in any volume-limited sample (Marzke & Da Costa 1997) and were probably even more numerous in the cosmological past (Ellis 1997). Thus a complete census requires a disproportionate amount of effort to be spent on finding and characterizing the faintest, most elusive galaxies.

The importance of dwarfs, however, extends far beyond the simple construction of a complete sample and the determination of, for instance, a luminosity function (though that exercise is interesting enough; see McGaugh 1996). The number and distribution of dwarfs relative to large galaxies constrains theories of galaxy formation, including the vexed questions of the biasing parameter (see, for example, Binggeli, Sandage, & Tammann 1988) and the rate of merging. Of cosmological importance, too, is the question of internal evolution; whether, for instance, dwarf irregular galaxies are just dwarf spheroidals undergoing starbursts, which would imply a variation of the luminosity-to-mass ratio with time (see Mateo 1998 for a discussion of this as well as most of the matters mentioned below).

The internal dynamics of dwarf galaxies give evidence of an unusually high ratio of dark to luminous matter (Mateo 1994; Hargreaves et al. 1996). This means not only that they are particularly useful laboratories for the study of the elusive dark mass, but they may also contain a significant fraction of all matter in the universe. The external dynamics of Local Group dwarfs has been used to measure the combined mass of the Group as well as its age, thus giving an independent figure for the age of the universe (Lynden-Bell 1981; Whiting 1999).

A dwarf galaxy provides a qualitatively different environment for star formation from a large galaxy (consider, for example, the escape speed of supernova-driven gas). Unsurprisingly, then, the known star formation histories of dwarf galaxies differ from those of larger objects. Interestingly, they also differ greatly from each other, to the point that no two dwarfs in the Local Group have the same history (Hodge 1994; Grebel 1997; Mateo 1998). The differences between them continue to challenge theorists.

The need for more data in all these matters, together with the relatively few known dwarf galaxies, make a search for more of them very worthwhile. However, almost by definition dwarf galaxies are difficult to detect and observe. Searches for them have been carried out in nearby galaxy groups (for example, Côté et al. 1997) with good results. However, owing to their small intrinsic size, dwarfs in external groups are difficult to characterize morphologically, and it is only within and near the Local Group that even the *Hubble Space Telescope* can obtain the resolved stellar photometry necessary for construction of detailed star formation histories. (Note also that in the most recent attempt at a volume-limited survey, Schmidt & Boller 1992, essentially all the galaxies fainter than $M_B = -11$ are in the Local

[1] Based on observations made with the Isaac Newton Telescope, operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias, and on observations made at Cerro Tololo Inter-American Observatory (CTIO). CTIO is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under a cooperative agreement with the National Science Foundation as part of the National Optical Astronomy Observatories (NOAO).

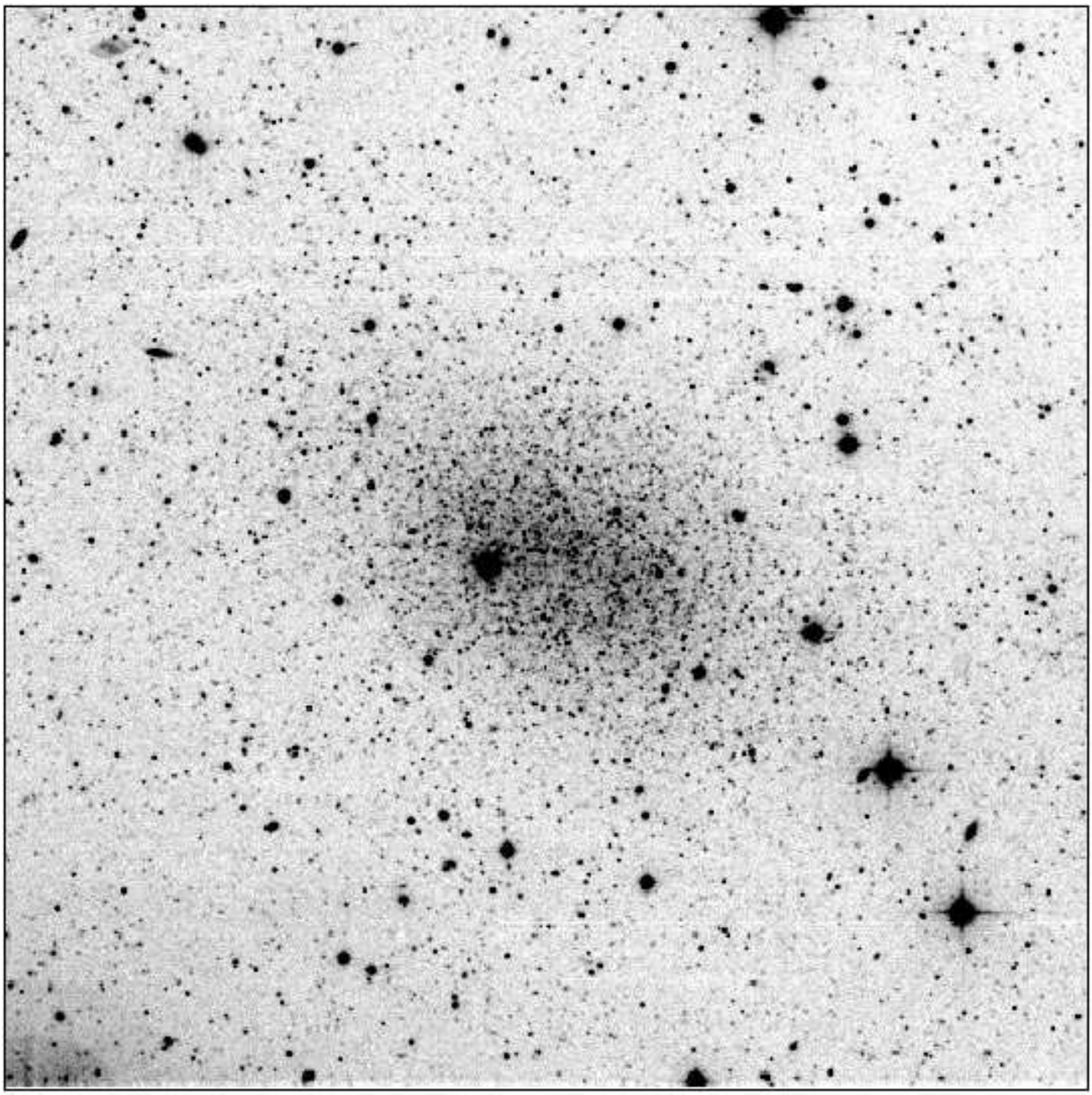

FIG. 1.—Combined V-band image of the Cetus dwarf with a total exposure of 1800 s taken using the Wide Field Camera on the 2.5 m Isaac Newton telescope on La Palma. The obvious visible stars in the dwarf galaxy are all red giants. North is to the top, and east to the left. The area shown is approximately $11' \times 11'$ corresponding to one-half of the central CCD of the four WFC CCDs.

Group itself.) Thus it appears most promising to limit a search to the Local Group and its immediate environs.

To this end a visual examination of all 894 fields covered by the ESO-SRC and SERC Equatorial surveys of the southern sky ($\delta < 3^{\circ}$) was performed. Objects resembling the Andromeda dwarf spheroidals and the Tucana dwarf, that is of very low surface brightness (VLSB), diffuse and large (1 to a few minutes of arc), were noted. Plate defects and Galactic reflection nebulosity were screened out by comparing blue and red plates of the same field. Objects noted by the UK Schmidt Telescope Unit during the survey (S. Tritton 1974, private communication), but not previously followed up, were also added to the list. Catalogs of known objects were consulted (chiefly the NASA Extragalactic Database, NED) and galaxies of high radial velocity as well as Galactic planetary nebulae were excluded. The final list numbered 75 candidates.

A previous discovery from this program, the dwarf galaxy in Antlia, was reported (Whiting, Irwin, & Hau 1997) at an intermediate stage of the project. We have now imaged all of our VLSB candidate objects, and here we report the discovery of a previously uncataloged Local Group dwarf galaxy in the constellation of Cetus.

In addition to our own wide field southern sky survey, recently two other large-area searches in the northern sky have been successful in finding nearby dwarf galaxies. Like

ourselves, Karachentseva & Karachentsev (1998) have used visual inspection but based on second epoch Palomar Sky Survey (POSSII) plates—although in practice film copies were actually used—to look for nearby galaxy candidates. This resulted (see Karachentsev & Karachentseva 1999) in the discovery of two new satellites of M31—And VI/Pegasus Dwarf as well as And VII/Cassiopaeia Dwarf, plus a series of more distant candidates. And VI was also discovered independently (Armandroff, Jacoby, & Davies 1999) using an automated search technique based on STSci digitized scans of the original POSSII plates. An additional M31 satellite, And V, of very low central surface brightness, had previously been found by the same authors using the automated technique (Armandroff, Davies, & Jacoby 1998).

2. FOLLOW-UP OBSERVATIONS

The majority of the objects from the VLSB list were imaged using the 1.5 m telescope at Cerro Tololo Inter-American Observatory (CTIO) with a thinned Tek 2048 × 2048 CCD as a detector. Some of the more northerly ones were followed up using the central CCD of the Wide Field Camera (WFC) on the 2.5 m Isaac Newton Telescope (INT) at the Observatorio del Roque de los Muchachos in the Canary Islands. At the f/13.5 Cassegrain focus of the 1.5 m CTIO telescope the scale is $0\farcs24$ pixel^{-1}, and the field coverage is just over $8' \times 8'$. The central thinned 4k × 2k EEV CCD on the INT WFC, mounted at prime focus, gives a spatial coverage of $22' \times 11'$ with a scale of $0\farcs33$ pixel^{-1}.

Candidates were initially examined by taking short, 15–20 minute, exposures in the R band. With the seeing typically between $0\farcs9$ and $1\farcs4$, this enables stellar objects to $R \approx 23$ to be detected. At this depth objects close to or within the Local Group should begin to resolve into stars, with the tip of the giant branch becoming readily visible. If a candidate appeared to resolve into stellar components, further broadband observations in V and I together with narrowband Hα were obtained. The raw CCD frames were processed in the standard way (bias-subtracted, trimmed, and flat-fielded using twilight flats taken during the observing run) in almost real time at the telescope to aid in visual inspection of candidates. A series of standard star fields taken from Landolt (1992) were observed at intervals throughout each night.

The initial exposure on 1998 August 27 of an uncataloged object in the constellation Cetus, at $\alpha = 00^{h}23^{m}38\fs7$, $\delta = -11°19'16''$ (B1950), or $\alpha = 00^{h}26^{m}11\fs0$, $\delta = -11°02'40''$ (J2000), showed a diffuse swarm of faint stars. Further exposures were taken in V, R, and I (totalling 2400 s in R and 3600 s in V and I) as well as Hα (1800 s). No significant emission regions were seen in the latter. Shortly after the CTIO run, on the nights of September 29 and 30, the INT plus WFC was used to take further deep images of Cetus (totalling 1800 s in V, 900 s in R, and 1500 s in I) in photometric conditions with seeing of about $1\farcs2$. The INT V and I frames consisted of a series of shorter exposures which were first bias-corrected, flat-fielded, and defringed (I only) and then co-aligned and stacked to remove cosmic rays. The combined INT WFC V-band image of Cetus is presented in Figure 1 and clearly shows the galaxy resolving into an amorphous swarm of stars typical of nearby dwarf spheroidal galaxies. (The bright object $1'$ to the east of center is a foreground star projected onto the dwarf.)

3. ANALYSIS

3.1. *Color-Magnitude Diagram*

The stacked V and I frames were analyzed using a PSF-fitting routine and the derived intensities mapped onto a total intensity system using aperture magnitudes of isolated unsaturated bright stars (Irwin 1985). A V, I color-magnitude diagram (CMD) constructed from the central $6'$ diameter region is shown in Figure 2 together with a comparison region from a neighboring field. The Cetus CMD shows a very clear giant branch extending from $I = 20.5$ to the limit of the data beyond $I = 22.5$. This feature is completely absent on neighboring WFC CCDs and also the upper and lower parts of the central CCD (not shown in Fig. 1). There is no clear indication of any red or blue supergiants, and that together with the absence of any obvious main-sequence population precludes any significant recent star formation. The morphology of the CMD is entirely compatible with that of the predominantly older population Local Group dwarf spheroidal systems. This is also consistent with the spatially smooth morphological appearance, and we conclude that the Cetus dwarf is an additional member of the dwarf spheroidal systems of the Local Group.

3.2. *Distance and Metallicity*

The locus of the giant branch provides a reasonably reliable way to estimate both the distance to Cetus and the metallicity of the dominant stellar population (Lee 1993; Lee et al. 1993). The apparent brightness of the tip of the giant branch is shown most clearly in the luminosity functions presented in Figure 3. From the clear rise in the luminosity function relative to a control region, we estimate I for the tip to be 20.5 ± 0.1. Located at Galactic coordinates $l = 101.5$, $b = -72.9$, Cetus is in a region of negligible extinction, according to the maps of Burstein & Heiles (1982). However, the higher resolution *IRAS*/DIRBE maps of Schlegel, Finkbeiner, & Davis 1998 indicate an extinction of $E(B-V) = 0.03$. Adopting this value for the reddening, with the caveat that the zero point of the *IRAS*/DIRBE system is on average 0.02 mag in $E(B-V)$ different from the Burstein & Heiles system and assuming $A_V = 3.2\ E(B-V)$ and $A_I = 1.9\ E(B-V)$ yields reddening corrections of 0.06 mag in I and 0.04 mag in $V-I$ color. The expected absolute magnitude of the giant branch tip is only weakly dependent on metallicity for the typical metal-poor populations of the Galactic dwarfs (Lee 1993), therefore taking this absolute magnitude to be -3.98 ± 0.05 and combining all the uncertainties we arrive at a distance modulus for Cetus of $(m - M)_0 = 24.45 \pm 0.15$, equivalent to a heliocentric distance of 775 ± 50 kpc.

The mean metallicity can be estimated from the median color, $V-I$, close to the tip of the giant branch at $M_I = -3.5$ (Armandroff et al. 1993) calibrated using Galactic globular cluster fiducial sequences. For Cetus, $V-I_{-3.5} = 1.35 \pm 0.05$, where the error includes a random contribution and an allowance for systemic uncertainties in the photometric color zero point. Correcting for the assumed reddening of 0.04 mag in $V-I$ yields a metallicity estimate of [Fe/H] $= -1.9 \pm 0.2$, with the error dominated by the uncertainty in the $V-I_{-3.5}$ color. We can also check the integrity of this estimate by comparing the giant branch locus of Cetus with other dwarf galaxies having similar published V, I CMDs. The closest match is provided by

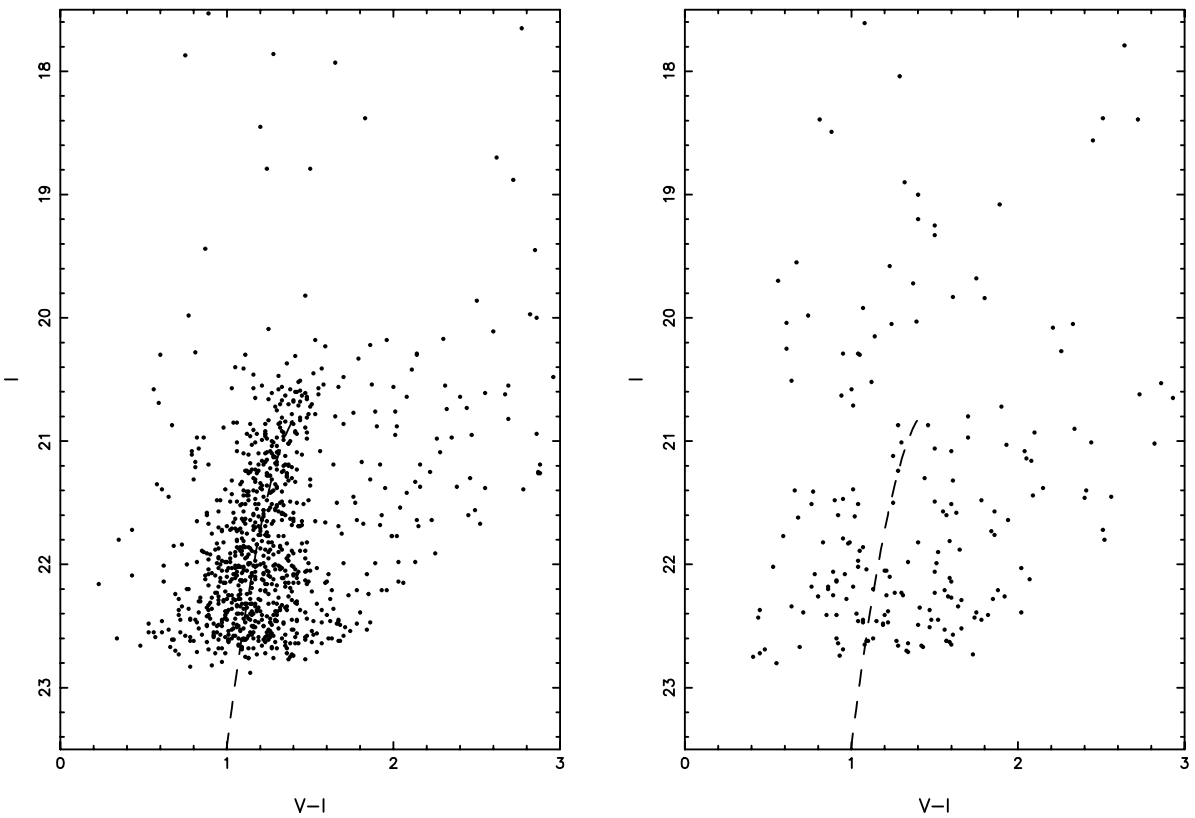

FIG. 2.—*Left*: V, I color-magnitude diagram for the Cetus dwarf derived from the central 6′ diameter region. *Right*: A neighboring comparison region with the same area. The red giant branch is clearly visible up to an I-band magnitude of 20.5. Objects brighter than $I = 20.0$ are Galactic foreground contamination, while those redward of $V-I = 1.6$ are either Galactic foreground stars or compact distant background ellipticals. The dashed line is the giant branch for the Galactic globular cluster NGC 6397 ([Fe/H] = −1.91), from Da Costa & Armandroff (1990), shifted to the same distance modulus and reddening.

Tucana, with [Fe/H] = -1.8 ± 0.2 (Saviane, Held, & Piotto 1996). A further check on the metallicity estimate is shown by the overplotted dashed line in Figure 2 of the fiducial giant branch of the Galactic globular cluster NGC 6397 with [Fe/H] = −1.91 (Da Costa & Armandroff 1990). For an $M_V = -10.1$ dwarf (see next section), the expected metallicity is [Fe/H] ≈ -1.8 (Da Costa et al. 1991), in good agreement with the value derived from the CMD.

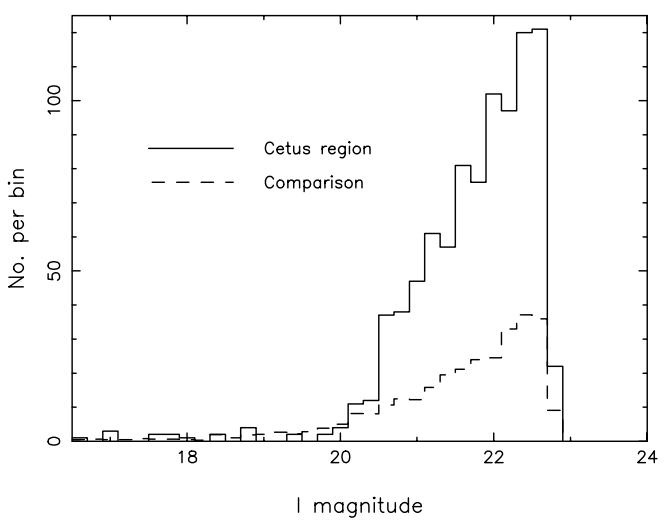

FIG. 3.—I-band luminosity function for a region centered on the Cetus dwarf, compared with a nearby region. The overabundance of stars starting at the tip of the red giant branch with I magnitude fainter than 20.5 is evident.

The apparent width of the locus of the giant branch of $\delta(V-I) \approx 0.25$ would correspond to a metallicity spread of roughly 1 dex; however, we caution against this direct interpretation since photometric errors in the color index $V-I$ vary from $\sigma(V-I) \sim 0.04$ at the tip of the giant branch, through $\sigma(V-I) \sim 0.06$ at $I = 21$ to $\sigma(V-I) \sim 0.10$ at $I = 22$, owing to a combination of PSF-fitting errors and the crowding effects of unresolved companions. It is possible that the entire locus broadening is caused by random measurement errors over the range $\pm 2\ \sigma(V-I)$; hence, at this stage we can place only a weak upper limit on the metallicity spread of 1 dex.

3.3. *Morphology and Magnitude*

The distribution of stars shown in Figure 1 shows no obvious concentrations, clusters, or irregularities. The smooth elliptical morphology is typical of the stellar appearance of Local Group dwarf spheroidal systems, such as Tucana (Lavery & Mighell 1992). Stellar images belonging to the red giant branch of Cetus are readily visible out to 4′ along the major axis, as is the contribution to the sky background from unresolved members of the dwarf galaxy.

The overall properties of the galaxy were estimated using a similar method to that described in Whiting et al. (1997). First, the effect of bright foreground stars and background galaxies was minimized by clipping the maximum allowed value of the intensity of the pixels in the V-band image to be

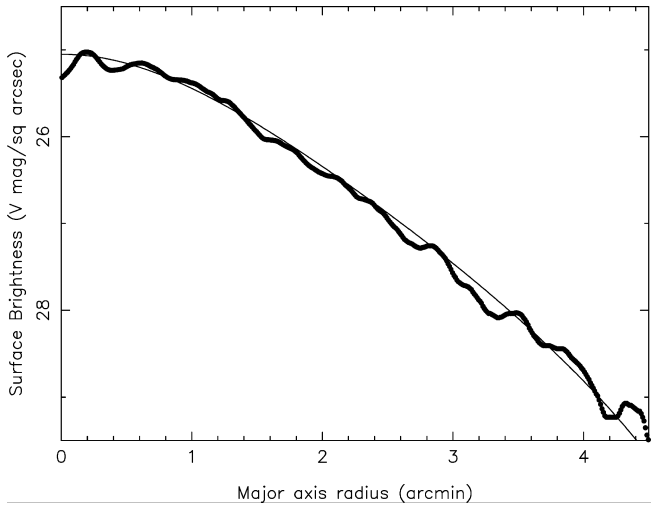

FIG. 4.—Major axis V-band radial surface brightness profile of the Cetus dwarf. Overplotted is a single-component King model fit with central surface brightness 25.1 mag arcsec^{-2}; core radius 1.9; and tidal radius 5.9.

the same as that for the brightest Cetus stars. Second, a flux-conserving Gaussian kernel was used to smooth the resulting pixel intensity distribution to a spatial resolution of $\approx 10''$. A standard intensity-weighted center-of-gravity and second-moment analysis was then used on this image to derive the centroid, ellipticity, and major axis position angle and its variation as a function of isophotal threshold. The shape parameters were then used to perform curve-of-growth integration relative to the sky background using a series of matched elliptical apertures. Finally, the average flux from the dwarf in a series of concentric elliptical annulii was used to estimate the major axis radial profile shown in Figure 4. A single-component King model (King 1962) fitted to this radial profile gives a convenient parameterization of the profile together with a robust estimate of the central surface brightness. All of the derived parameters are listed in Table 1. A similar analysis was performed in the I band but, owing to the residual low-level fringing, does not reach to as low a limiting surface brightness and hence gave less reliable morphological results.

TABLE 1

DATA FOR THE CETUS DWARF GALAXY

Parameter	Value
Identification	Cetus dwarf spheroidal WHI B0023-11
Position (B1950) ($\pm 10''$):	
R.A.	00 23 38.7
Decl.	−11 19 16
Galactic l	101.5
Galactic b	−72.9
Ellipticity	0.35 ± 0.03
Position angle	70 ± 2
Apparent magnitude:	
m_V	14.4 ± 0.2
m_I	13.5 ± 0.2
Extinction:	
$E(B-V)$	0.03
A_V	0.10
Distance:	
$(m-M)_0$	24.45 ± 0.15
kpc	775 ± 50
LG center	615 ± 40
Metallicity [Fe/H]	−1.9 ± 0.2
Absolute magnitude:	
M_V	−10.1
M_I	−11.0
Radial profile (geometric mean):	
Σ_0, v mag arcsec^{-2}	25.05 ± 0.1
Core radius (r_c) (arcmin)	1.5 ± 0.1
Tidal radius (r_t) (arcmin)	4.8 ± 0.2

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

4. DISCUSSION

The central surface brightness of Cetus, measured using the King model fit to be 25.05 ± 0.1 mag arcsec^{-2} in the V band, lies at the faint end of the central surface brightness distribution for Local Group dwarf spheroidals, probably explaining why Cetus had not been previously noted. The core and "tidal" radii of 350 and 1120 pc, respectively (geometric means of major and minor axes), are also indicative of the diffuse nature of the galaxy. Of the Galactic dwarf spheroidals, only Fornax has a larger core radius, but it has a central surface brightness some 2 mag brighter. The concentration index $c = 0.51$ is, however, typical of Local Group dwarf spheroidal systems, and Cetus lies right on the locus of central surface brightness versus absolute luminosity for these objects (e.g., Saviane et al. 1996).

The integrated apparent V magnitude of $m_V = 14.4$ together with the distance modulus derived previously yield an absolute magnitude of $M_V = -10.1$. This is toward the faint end of the Local Group luminosity function and comparable with the isolated Local Group galaxy Tucana, estimated to have an absolute V-band magnitude of $M_V = -9.6$ by Saviane et al. (1996).

The extragalactic database, NED, lists nothing within 4′ of the position of Cetus, and the *IRAS* 60 μm maps show nothing here either. No extant radio cataloges list anything close to the position. The nearest compact high-velocity H I cloud (HVC) in the compilation of Braun & Burton (1999) is 5° away. In the more complete list of HVCs from Wakker & van Woerden (1991), the nearest HVC is at $l = 102.5$, $b = -72.0$, some 1.4 away on the sky. However, this object has a Galactic infall velocity of −237 km s^{-1} and is highly unlikely to be associated with the Cetus dwarf.

The HIPASS blind H I survey presently being conducted (see Banks et al. 1999) could in principle detect Cetus in the radio band, but the absence of any obvious current star formation makes it unlikely that there is enough H I gas present to allow this.[2]

The distance to Cetus places it about 175 kpc total distance from the Local Group galaxies WLM (7.3 away on the sky) and about 230 kpc total distance from IC 1613[3] (16.3 away on the sky); it is therefore highly likely to be a member of the Local Group. The location of Cetus with

[2] Preliminary attempts to detect Cetus in the HIPASS survey (R. C. Kraan-Korteweg 1999, private communication) have revealed nothing at the position of the dwarf.

[3] Assuming distances to IC 1613 and WLM of 765 and 940 kpc, respectively; see Hodge (1994) and references therein.

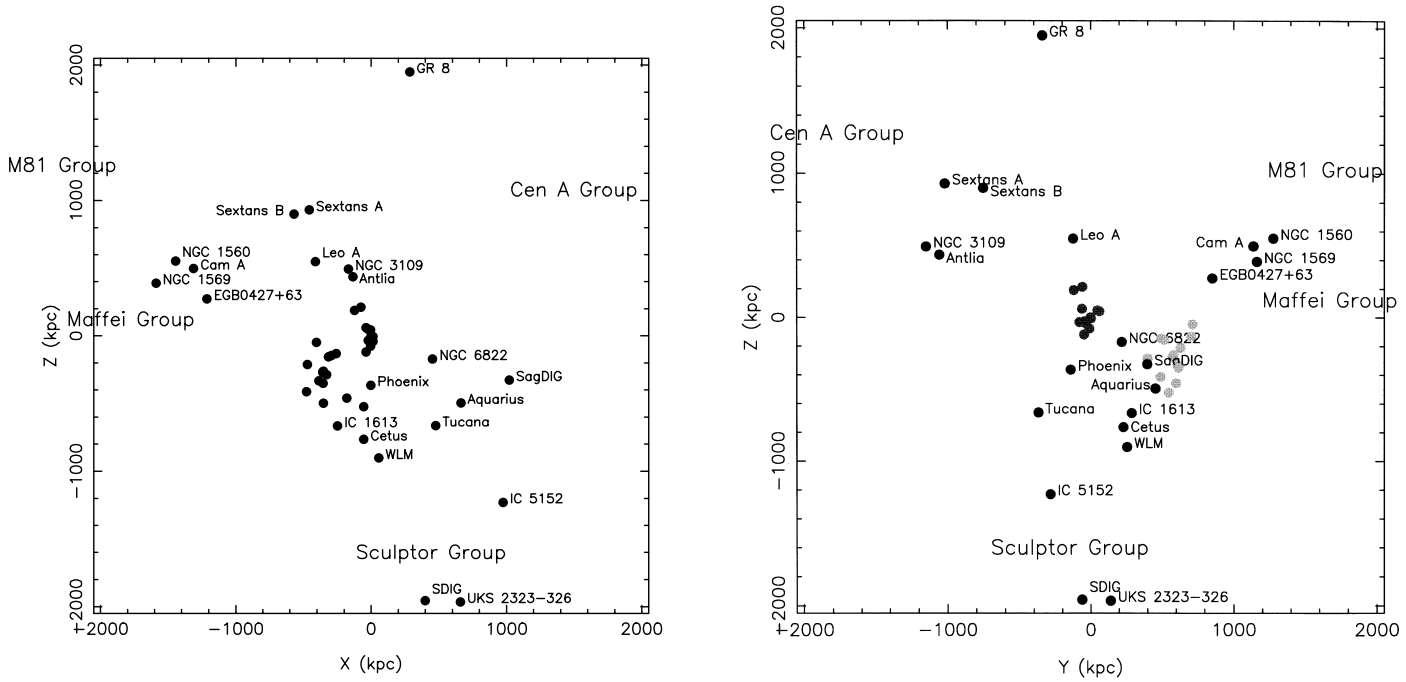

FIG. 5.—Distribution of Local Group galaxies plus neighboring galaxies and groups in X-Z, Y-Z Galactic coordinates. The newly discovered Cetus dwarf galaxy lies in the general direction of the elongation of the Local Group toward the Sculptor Group. The objects near the origin are the Galaxy and its satellite system, while M31 and its satellites are clustered around (−400, −500, −300). Most remaining nearby galaxies appear to be in loose associations often stretching toward other external galaxy groups.

respect to other Local Group members and other nearby groups is shown in Figure 5. Without a radial velocity we have no way of telling if Cetus is directly associated with either WLM ($V_H = -116$ km s^{-1}) or IC 1613 ($V_H = -236$ km s^{-1}). However, Cetus does appear to be another member of a general concentration of Local Group outer satellites stretching along the direction toward the Sculptor Group (see Fig. 5). In contrast to the majority of early-type dwarfs in the Local Group, which are satellites of the two major galaxies, Cetus lies in a relatively isolated region and is probably most comparable to Tucana.

Although Cetus is visible to the eye on the SERC IIIa-J survey plates, it has not to our knowledge been noticed or cataloged previously probably owing to its low central surface brightness and diffuse appearance. The visibility of Cetus on the discovery UKST survey plate is illustrated in Figure 6. The brightest stars from the galaxy just begin to resolve at the limit of the survey plate, but it is the large amorphous low surface brightness patch of unresolved stars that the eye detects. This characteristic is typical of good candidate Local Group galaxies from our survey. We have surveyed all 894 UKST IIIa-J survey plates for the southern sky in a consistent way and have available detailed CCD imaging of all of our VLSB candidate objects. It is interesting that apart from the (re)discovery of Antlia (Whiting et al. 1997) Cetus is the only unambiguously bona fide Local Group galaxy found. Even though we have deep CCD imaging of candidates of comparable or even fainter central surface brightness over the whole of the southern sky, only a handful of nearby galaxies have been found in total. With the caveat that it is difficult to work in regions close to the Galactic plane, this suggests to us that the census of Local Group galaxies is not catastrophically incomplete and that the faint end of the Local Group luminosity function is significantly flatter than predicted by comparison with external clusters (Phillipps et al. 1998; Trentham 1998) or from theoretical arguments of the hierarchical growth of structure in CDM universes (Klypin et al. 1999).

Without any velocity measurements, nothing can be said definitely about the dynamics, internal or external, of the Cetus dwarf. As noted previously, velocities based on H I data may be impossible to obtain. In that case, time on the largest aperture telescopes will be required to obtain optical velocities from its stars.

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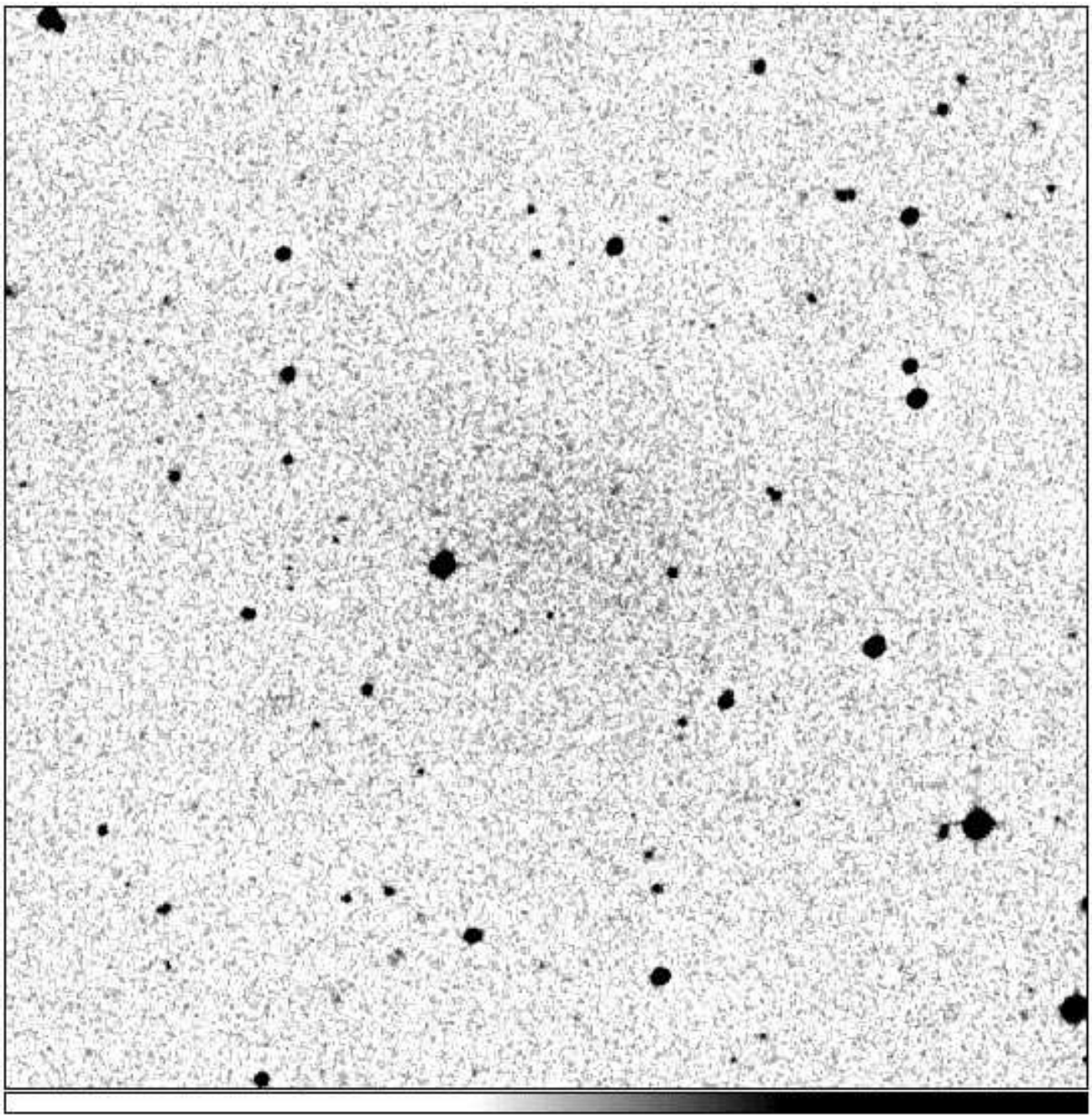

FIG. 6.—An 8′ × 8′ region centered on the Cetus dwarf taken from the discovery UKST IIIa-J sky survey glass copy plate; north is to the top, and east is to the left. The galaxy is just starting to resolve at the limit of the plate but is readily detected owing to its amorphous low surface brightness appearance spread over several arcminutes (millimeters). This characteristic is typical of good candidate Local Group galaxies from our survey.

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