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Hα OBSERVATIONS OF FOUR NOVAE IN M31

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ABSTRACT

On-line off-line Hα plates of M31's nucleus revealed four bright stellar objects ($m_R \approx 14.9$, 15.0, 15.8, 16.4) within 1.2 kpc of the galaxy center. Spectrophotometric observations made 10 days later showed the stars were novae in the stage of early decline. In the 10 day interval, the Hα emission from these novae faded less than a magnitude, despite the fact that their continua had long since faded from view. The high luminosity and long decay time of the Hα emission suggest it might make an excellent standard candle for extragalactic distance measurements.

Subject headings: galaxies: individual — stars: novae

I. INTRODUCTION

Novae are among the best and brightest primary standard candles for extragalactic distance measurements (de Vaucouleurs 1978*a*, *b*). They are, however, difficult to study in our Galaxy. Specifically, the problems associated with deriving distances, along with the uncertainties about the intervening interstellar material, make calibration of novae difficult. To date, the primary calibrations are based largely on 15 well-observed galactic novae.

A large and homogenous nova sample is readily available for secondary calibration, however. Partial light curves for over 100 novae exist from surveys of M31 by Hubble (1929), Arp (1956), and Rosino (1964, 1973). These data reveal a tight relation between a nova's absolute brightness and its fade rate. It is this property that has been used to estimate distances to several nearby galaxies.

Hubble (1929) made his survey with blue-sensitive photographic plates, the only plates available at that time. For consistency Arp (1956) also made a blue survey when he extended Hubble's work. Rosino (1964, 1973), however, achieved a gain in contrast over the background galaxy by using a broadband ultraviolet color to detect M31's novae. In both these colors the brightest novae are visible for only a few days. Consequently, daily monitoring is needed to define U and B light curves.

A bright continuum is not the only nova signature. Shortly after maximum light, novae develop strong, broad Balmer emission lines. Although this emission starts fading immediately, its characteristic decay time ($t_f = L/\dot{L}$) is longer than that for the continuum. Observations of galactic novae by Popper (1940), Meinel (1963), Younger (1980), Klare, Wolf, and Krautter (1980), and others show that in the days or weeks after maximum, a 4 or 5 mag difference between Hα and the continuum is not uncommon. It is plausible, therefore, that the Hα emission of novae may be a better and longer lasting standard candle than the continuum.

In this paper we report the discovery of four novae near the center of M31, detected soley from their Hα emission. We describe in § II the method used in this detection and our spectrophotometric observations of the novae. In § III we detail the spectral characteristics of each nova and estimate the evolutionary state of their light curves at the time of our observations. In § IV we estimate the length of time these objects could have been detected through their Hα emission. We conclude by discussing the possibility of using Hα emission as an extragalactic standard candle.

II. OBSERVATIONS

On 1981 September 25 and 26, we surveyed the nucleus of M31 for Hα emission line objects with the Carnegie two-stage image tube at the f/7.5 focus of the Kitt Peak No. 1 0.9 m telescope. We took two pairs of baked IIIa-J plates sequentially through on-line and off-line interference filters (Ford, Jenner, and Epps 1973). The on-line filter had a 27 Å full width half-maximum transmission (FWHM) in the telescope's converging beam and a central wavelength of 6563 Å. The off-line filter's central wavelength was 6204 Å with a 150 Å FWHM. The exposure times of the plate pairs were chosen to balance the limiting magnitude on the plates. The photographic observations are summarized in Table 1.

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TABLE 1

SURVEY PLATES OF M31 NUCLEUS

Plate Number	UT Date	Filter	Exp. Time (min)
6384	1981 Sep 25	6563/27	30
6385	1981 Sep 25	6204/150	3.75
6402	1981 Sep 26	6563/27	15
6403	1981 Sep 26	6563/27	7.5
6404	1981 Sep 26	6204/150	2
6405	1981 Sep 26	6204/150	1

A comparison of our plate pairs revealed four bright, stellar sources which were completely invisible on the continuum plates. Inspection of plates taken a few years earlier proved the sources were new; none appeared on Hα plates taken with the Palomar 48 inch (1.2 m) Schmidt by Arp in 1964, and none were visible on Lick 3 m 5007 Å plates taken in 1976 (Ford and Jacoby 1978). All four sources were located within 1.2 kpc of M31's center and were quite luminous—more luminous than any planetary nebula associated with the galaxy. Our 15 minute Hα plate and its companion continuum exposure are reproduced in Figure 1 (Plates 7 and 8).

The coordinates of the four sources are listed in Table 2. These coordinates were derived from a multilinear regression on the x-y positions of secondary standard stars measured by Ford and Jacoby (1978). The standard errors in these positions are $\sim 1''$.

The Hα sources were observed with the Lick image-tube scanner (ITS; Robinson and Wampler 1972*a*, *b*; Miller, Robinson, and Wampler 1976; Miller, Robinson, and Schmidt 1980) at the Cassegrain focus of the Shane 3 m telescope on the nights of 1981 October 4 and 5. The "red" image-tube chain, which has an S-25 photocathode and maintains a high sensitivity at Hα, was used for these spectrophotometric observations. Data were obtained with two gratings, a 600 lines mm^{-1} and a 1200 lines mm^{-1} grating, both blazed at 5000 Å in first order. The 600 lines mm^{-1} grating with the ITS yielded spectra with ~ 11 Å resolution. The resolution obtained with the 1200 lines mm^{-1} grating was roughly half this value. These observations are summarized in Table 3.

The spectrophotometric observations were reduced using the UCLA FORTRAN Scanner Data Reduction System (FSDRS; Grandi 1982). Pixel-to-pixel detector irregularities were removed by dividing the raw data by a continuum lamp spectrum taken at the beginning and ending of each night. Wavelength calibrations were determined from fifth-order polynomial least square fits to comparison lamp spectra obtained at the telescope position of each object. The effects of atmospheric extinction were removed using the mean extinction coefficients for Mount Hamilton.

We used the large aperture (10″) Lick scans to derive accurate absolute fluxes for each Hα source. First, instrument response curves were derived from observations of standard stars calibrated by Stone (1977) and Oke (1974). These observations were taken through the large aperture to ensure that all the light from the star was collected. The response curves were applied to each Hα source to derive the relative flux at each wavelength. The relative flux in the Hα line was then assumed to be absolute for the observation taken through the large aperture, and the small aperture observations were scaled to match this value. The nights in which these observations were obtained were photometric with less than 2″ seeing. We estimate the errors in our absolute fluxes to be no larger than ~ 0.1 mag.

III. SPECTROSCOPIC RESULTS

The ITS spectra of the Hα sources are shown in Figure 2. Figure 3 reproduces our high-resolution Hα spectra for objects 2 and 3. All of these objects are classical novae, in the stage of development labeled by McLaughlin (1936) as early decline. Qualitatively, all of the spectra are similar.

A very broad ($\gtrsim 50$ Å FWHM), structured Hα emission line dominates each spectrum. This line appears to have two components: a moderately sharp feature to the red and a band of emission roughly twice as broad to the blue. Hβ, the next brightest line, exhibits the same structure, but it is more than 5 times fainter. Weaker lines of Fe II (Revised Multiplet Table 42) at $\lambda\lambda$4923, 5018, and 5169 also appear in each object.

Novae 1, 3, and 4 have two other interesting lines. An emission band arising from a blend of O II, N II, and N III is readily apparent at $\lambda \sim 4640$ Å in each of these spectra. In addition, weak, broad [O I] λ6300 emission is detectable. No trace of these lines is seen in

TABLE 2

Hα OBJECTS

OBJECT	R.A. (1975.0)	DECL. (1975.0)	PROJECTED DIST. FROM NUCLEUS		Hα FWHM (km s^{-1})	Hα/Hβ	m_B (Sharov)
			Angle	kpc			
Nova 1	$00^{h}40^{m}56^{s}.88$	$41^{\circ}05'02''.1$	$5'38''$	1.13	2750	7.5	~ 20
Nova 2	00 41 18.72	41 10 01.9	2 03	0.41	1900	5.0	~ 19.5
Nova 3	00 41 36.29	41 10 48.3	3 50	0.77	2700	7.0	~ 21.5
Nova 4	00 41 43.99	41 05 46.8	4 44	0.95	2880	5.5	~ 19.5

TABLE 3

SPECTROPHOTOMETRIC OBSERVATIONS

Object	Date	UT	Instrument	Grating (lines mm^{-1})	Coverage (Å)	Standard Star	Aperture (″)	Int. Time (min)
Nova 3	1981 Oct 4	7:15	Lick ITS	600	4500–7100	Feige 25	3	48
Nova 3	1981 Oct 4	8:00	Lick ITS	600	4500–7100	Feige 25	10	16
Nova 3	1981 Oct 4	8:50	Lick ITS	600	3800–5500	Feige 25	3	24
Nova 2	1981 Oct 5	6:30	Lick ITS	600	4500–7100	BD +28°4211/HZ 15	3	48
Nova 2	1981 Oct 5	7:30	Lick ITS	600	4500–7100	BD +28°4211/HZ 15	10	16
Nova 2	1981 Oct 5	8:00	Lick ITS	1200	6000–7200	HZ 15	3	24
Nova 3	1981 Oct 5	8:45	Lick ITS	1200	6000–7200	HZ 15	3	24
Nova 3	1981 Oct 5	9:30	Lick ITS	600	4500–7100	BD +28°4211/HZ 15	3	32
Nova 3	1981 Oct 5	9:55	Lick ITS	600	4500–7100	BD +28°4211/HZ 15	10	16
Nova 4	1981 Oct 5	10:45	Lick ITS	600	4500–7100	BD +28°4211/HZ 15	3	48
Nova 4	1981 Oct 5	11:30	Lick ITS	600	4500–7100	BD +28°4211/HZ 15	10	16
Nova 1	1981 Oct 5	12:15	Lick ITS	600	4500–7100	BD +28°4211/HZ 15	3	32
Nova 3	1981 Oct 24	10:30	Kitt Peak IIDS	500	4800–6900	EG 50	3.2	40
Star *a*	1982 Jan 31	2:15	Mt. Lemmon ITS	1200	5400–6800	Feige 25	7	8
Star *b*	1982 Feb 2	2:30	Mt. Lemmon ITS	1200	5400–6800	Feige 15	7	16
Star *a*	1982 Feb 2	2:45	Mt. Lemmon ITS	1200	5400–6800	Feige 15	7	24

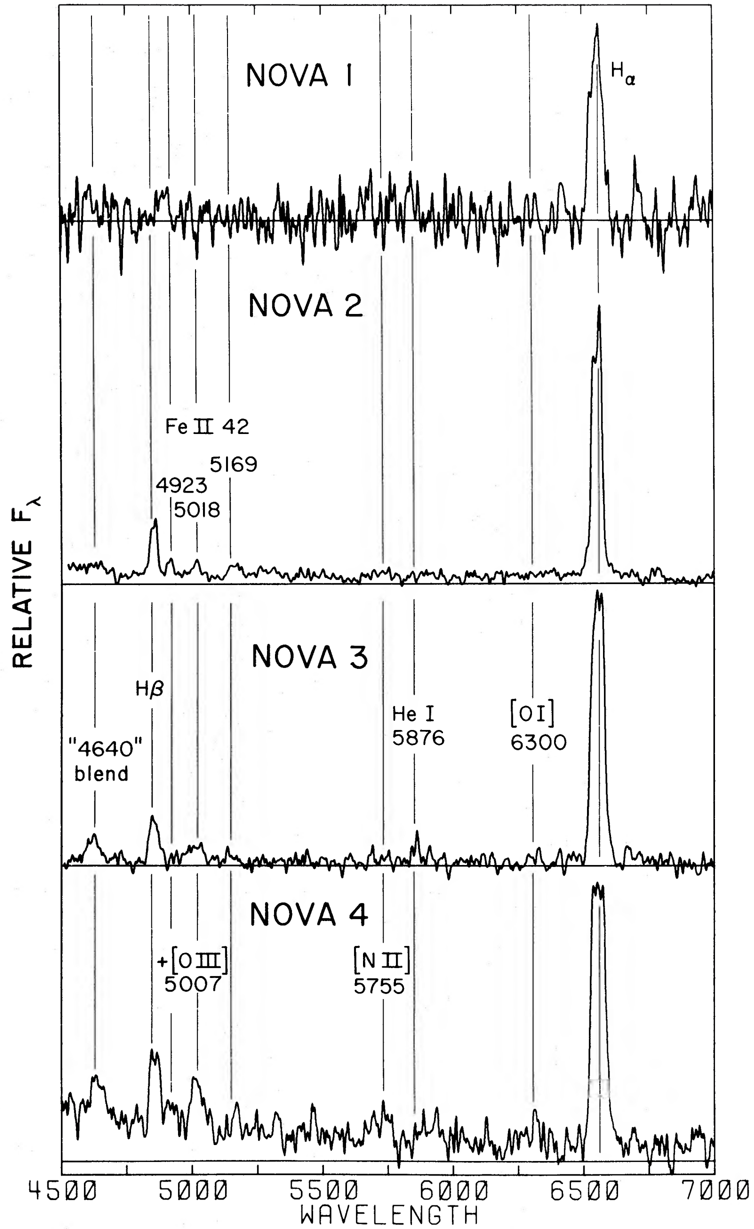

FIG. 2.—The spectra of the four novae observed at Lick Observatory. The data have been convolved with a Gaussian (FWHM 3.75 Å) in order to suppress high-frequency noise. The apparent continuum seen in nova 4 is caused by poor subtraction of the background galaxy.

nova 2, despite it's being the brightest nova and the only one with a possible continuum measurement.

At the time of our observations the novae were well past maximum light. Because of the difficulty in subtracting the bright background galaxy, our spectrophotometry only places an upper limit on the underlying nova continuum. Sharov (1982) obtained photographic *B*-magnitudes for the novae on 1981 September 28 (cf. Table 2), but these, too, are uncertain. McLaughlin (1942, 1960), however, has noted that despite large differences in the speed of a nova's spectral development, the development is correlated with the number of magnitudes it has declined from maximum light. Table 4 summarizes the relevant parts of this relation. Although the relation is only approximate and some systematic differences between fast and slow novae do exist, the spectral development can still be used to estimate the amount of continuum fading that must have taken place before our spectral observations. Each nova is discussed below.

a) *Nova 1*

This is the faintest of the four novae. The blend at 4640 Å is clearly evident, but the signal-to-noise ratio

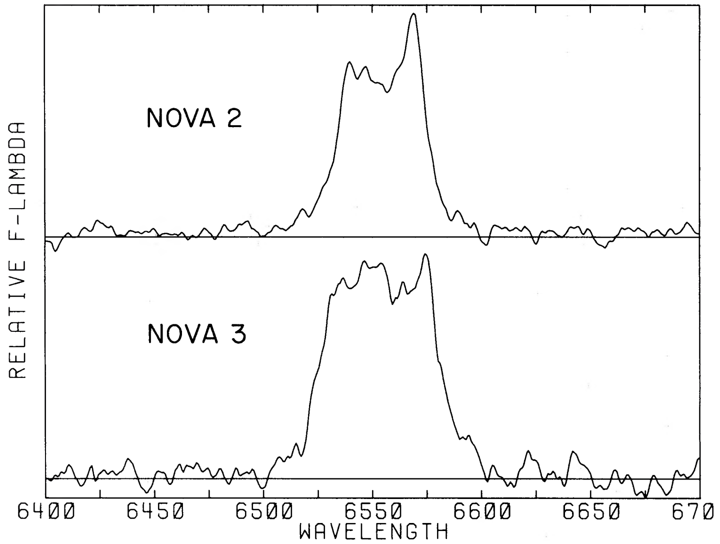

FIG. 3.—The Hα line profiles of novae 2 and 3 convolved with a FWHM 1.5 Å Gaussian. Multiple components in both lines are obvious.

is too poor to detect weaker lines with confidence. We can only state that this nova must have faded at least 3 mag before our observation.

b) *Nova 2*

This nova is the brightest of the four. It is also the only nova in which we have a possible continuum detection ($m_R \approx 18.9$). The two-component Balmer emission places a lower limit on the amount of decline. The narrower red component arises from the principal emission system; the broad, blue component belongs to the diffuse enhanced spectrum. The upper limit is derived from the lack of emission from [O I] λ6300 or λ4640. This nova must therefore only be 1.5–2.5 mag down from maximum. Interestingly, this implies its continuum brightness at maximum was only $m_R \geq 16.5$, over a magnitude fainter than the recorded Hα magnitude.

c) *Nova 3*

There is weak [O I] as well as strong λ4640 emission, indicating the nova has entered its so-called Orion stage. He I λ5876 is apparent in the Lick spectra, though [N II] λ5755 is not. The continuum of this nova is therefore probably ~3.5 mag fainter than at maximum.

TABLE 4

STAGES OF NOVA EMISSION-LINE SPECTRUM

Stage	$m - m_{\max}$
Appearance of diffuse enhanced spectrum	1.2
Maximum of diffuse enhanced spectrum	2.0
[O I] flash	2.6
Appearance of λ4640 blend	3.0
[N II] flash	3.3
Helium flash	3.6
[O III] emission first traced	3.7
$\lambda 4949 \approx \lambda 4924$	4.4

Nova 3 was also observed with the Kitt Peak intensified image dissector scanner 20 days later. Hα, though still dominating, had faded significantly. [N II] λ5755 and He I λ5876 were detected, but the signal-to-noise ratio was not high enough to state anything about [O III]. It is probable that ~1 mag of additional continuum fading had taken place between this and the previous observation.

d) *Nova 4*

The λ4640 blend, [N II] λ5755, and He I λ5876 are all detectable in this spectrum, though the last two features are weak. The λ5018 Fe II line appears to be too strong when compared with the other lines of its multiplet. It is likely that this line contains a contribution from [O III] λ5007. The [O III] λ4959 line, however, has not yet reached the intensity of the Fe II lines. This evidence indicates that the nova has probably declined ~4 mag from maximum.

The Hα fluxes measured from our spectrophotometric observations are listed in Table 5. We derived Hα magnitudes from these spectra by averaging the flux in a 27 Å bandpass centered on 6563 Å. The zero point for this measurement was chosen to agree with that of the *R* filter calibrated by Hayes (1979). Table 5 lists these magnitudes.

IV. THE Hα DECAY TIME

The rate of fading of nova continua is well known. Light curves presented by Hubble (1929), Arp (1956), and Rosino (1964, 1973) show that those novae in M31 reaching $m_B \sim 16$ typically fade 3 mag within a week. The time required for comparable fading in Hα, however, has never been investigated. In order to estimate this

1983ApJ...272...92C

TABLE 5

Hα MAGNITUDES

Object	Date	Total Hα Flux (ergs cm^{-2} s^{-1})	$m_{H\alpha}$[a]
Nova 1	1981 Sep 26	...	16.4
	1981 Oct 5	1.28×10^{-14}	17.4
Nova 2	1981 Sep 26	...	14.9
	1981 Oct 5	9.24×10^{-14}	15.1
Nova 3	1981 Sep 26	...	15.0
	1981 Oct 4	6.25×10^{-14}	15.6
	1981 Oct 5	5.55×10^{-14}	15.9
	1981 Oct 24	1.93×10^{-14}	16.9
Nova 4	1981 Sep 26	...	15.8
	1981 Oct 5	2.91×10^{-14}	16.7

[a] $m_{H\alpha}$ of 0.0 = 2.78×10^{-20} ergs cm^{-2} s^{-1} Hz^{-1}.

quantity, we combined our spectrophotometric Hα fluxes with magnitudes measured off our photographic survey plates. These magnitudes were derived as follows:

Regions around the novae and several field stars were digitized with the Kitt Peak PDS microdensitometer. Calibration plates taken at the telescope were used to transform the recorded density to intensity. The RICHFLD stellar photometry program (Tody 1980) and the Kitt Peak interactive picture processing system (IPPS) were then used to find raw photographic magnitudes.

The zero points for the plates were set with ITS spectrophotometry of field stars using the Mount Lemmon University of Minnesota/University of California at San Diego 1.5 m telescope. Two stars on our plates (marked *a* and *b* in Fig. 1*a*) were observed and reduced using the methods and routines described in § II. The absolute fluxes in the 27 Å bandpass centered on 6563 Å were averaged and Hα magnitudes established as in § III. Star *a*'s magnitude was used to define the absolute scale for the plates, and the novae photographic magnitudes were scaled to this value. These magnitudes are listed in Table 5.

This procedure is susceptible to two types of errors: those introduced through the ITS spectrophotometry and those caused by image-tube distortion of the stellar images. We can estimate the spectrophotometric errors by comparing our standard star magnitudes with independently derived photographic magnitudes.

The stars used as standards were so chosen because they were also secondary *V*-magnitude standards for Arp's (1956) nova survey (star *a* = Arp 1-a, star *b* = Arp 1-b). To test the accuracy of our spectrophotometry, we performed the appropriate summation of the standard star stellar fluxes using the *V* filter response given by Sandage and Lewis (1963), and applied the *V*-magnitude zero point quoted by Hayes (1979). Although our spectrophotometry did not cover the entire range of the *V* band, the spectral information we did obtain allowed us to extrapolate over the missing region. The desired *V*-magnitudes for both standards were within 0.05 mag of the values assigned by Arp. The error from our spectrophotometry, therefore, appears to be small.

The RICHFLD stellar photometry program solves for a magnitude by fitting a program star with a point spread function derived from field star profiles. Consequently, the Carnegie image tube S-distortion can introduce an error into the magnitude solution. Unfortunately, this error depends on plate location and is difficult to quantify. However, an estimate of the total error resulting from matching our photographic and spectrophotometric magnitudes can be made from our measurements of star *b*. This star happens to have a particularly asymmetrical profile and a correspondingly large measurement error. Our photographic Hα magnitude for this star is 14.13, 0.17 mag brighter than our spectrophotometric magnitude. Based on this, we assign 0.2 mag to be the maximum error in our magnitude measurements.

Even with this measurement error and our limited number of observations, it is clear that each nova was detectable in Hα for several weeks. While it is difficult to quantify each object's Hα light curve from these observations, we can, at least, estimate the time the Hα emission was observable. Our initial observation was a 30 minute image-tube photograph taken on 1981 September 25. At that time the continua of all four novae were undetectable on our off-band plate. If we assume the light curves for these novae were similar to those of other M31 novae observed by Arp (1956) and Rosino (1964, 1973), this implies the novae must have been at least one week old when first detected. Novae 1 and 4 were, in fact, probably older than this, as their spectra indicate substantial fading had taken place before our spectrophotometry.

Although novae can have widely different speeds, the Hα decay rates of our four novae appear to be similar. The rates suggest novae 1 and 4 could have been followed for another week or two past our last observation. Nova 3 was observed and measured a full month after its first detection. It is therefore probable that all of these novae could have been detected in Hα for over a month, and possibly for as long as two months. This is at least twice as long as would be possible using a broadband filter.

An independent estimate of the Hα decay time is possible using the fairly well determined value for the frequency of novae in M31. From the data presented by Hubble (1929), Arp (1956), and Rosino (1973), the observed nova rate in M31 is ~ 20 yr^{-1}, with 70% of the novae occurring within 9′ of the nucleus. The simultaneous observation of four novae, therefore, implies a typical nova decay rate in Hα of ~ 3.5 months. This rate is in rough agreement with that estimated above.

V. DISCUSSION

The large Hα flux suggests the possibility of using this emission as a standard candle in extragalactic distance determinations. De Vaucouleurs (1978*a*, *b*) and others have noted that the absolute magnitude–decay rate relationship for nova continua makes an excellent standard candle. One of the major difficulties in using this correlation is the relatively short-lived nature of this emission—the brightest novae decline several magnitudes from maximum in a matter of days. Daily monitoring is therefore needed to study a representative sample of these objects.

Because of its long lifetime and its extremely broad line width (over 50 Å, or 2500 km s^{-1} at half-maximum), a nova's Hα emission appears to be a potentially more useful quantity to measure than the continuum. If the Hα absolute magnitude and decay rate are as well correlated as that of the continuum, this emission line offers the possibility of yielding reliable distance determinations from weekly, rather than daily, observations.

There is one disadvantage to using Hα magnitudes in distance determinations. A typical early-type galaxy may be 2 mag brighter in the red than in the ultraviolet. A nova's contrast relative to its surroundings is, therefore, decreased by that much. It is likely, however, that a nova's Hα monochromatic luminosity surpasses that of its continuum at maximum. Observations of V1500 Cygni (Duerbeck and Wolf 1977) show this nova's Hα emission 1 day after maximum to be almost a magnitude brighter than the maximum continuum level. Similarly, the Hα flux of Nova Cygni 1978 3 days after maximum exceeded the continuum emission at maximum by about a magnitude (Klare, Wolf, and Krautter 1980). At the time of detection, novae 2 and 3 had magnitudes corresponding to a monochromatic flux of 3×10^{-26} ergs cm^{-2} s^{-1} Hz^{-1} at the Earth (cf. Table 5). According to the absolute calibration given by Hayes (1979), this flux is equivalent to a *U*-magnitude of 14.4, or a *B*-magnitude of 15.5. This is brighter than any nova discovered in the M31 surveys by Arp (1956) or Rosino (1964, 1973). For interference bandwidths of 50 Å or less, the higher luminosity of the background galaxy at Hα is therefore not as severe a hindrance as might otherwise be estimated.

The evidence suggests that the Hα emission novae may potentially make an excellent standard candle for extragalactic distance measurements. This emission is at least as bright as that from nova continua, and the decay rate is apparently much slower. If a calibration for the absolute magnitude can be found, this property will present a powerful tool for distance determinations to nearby groups of galaxies.

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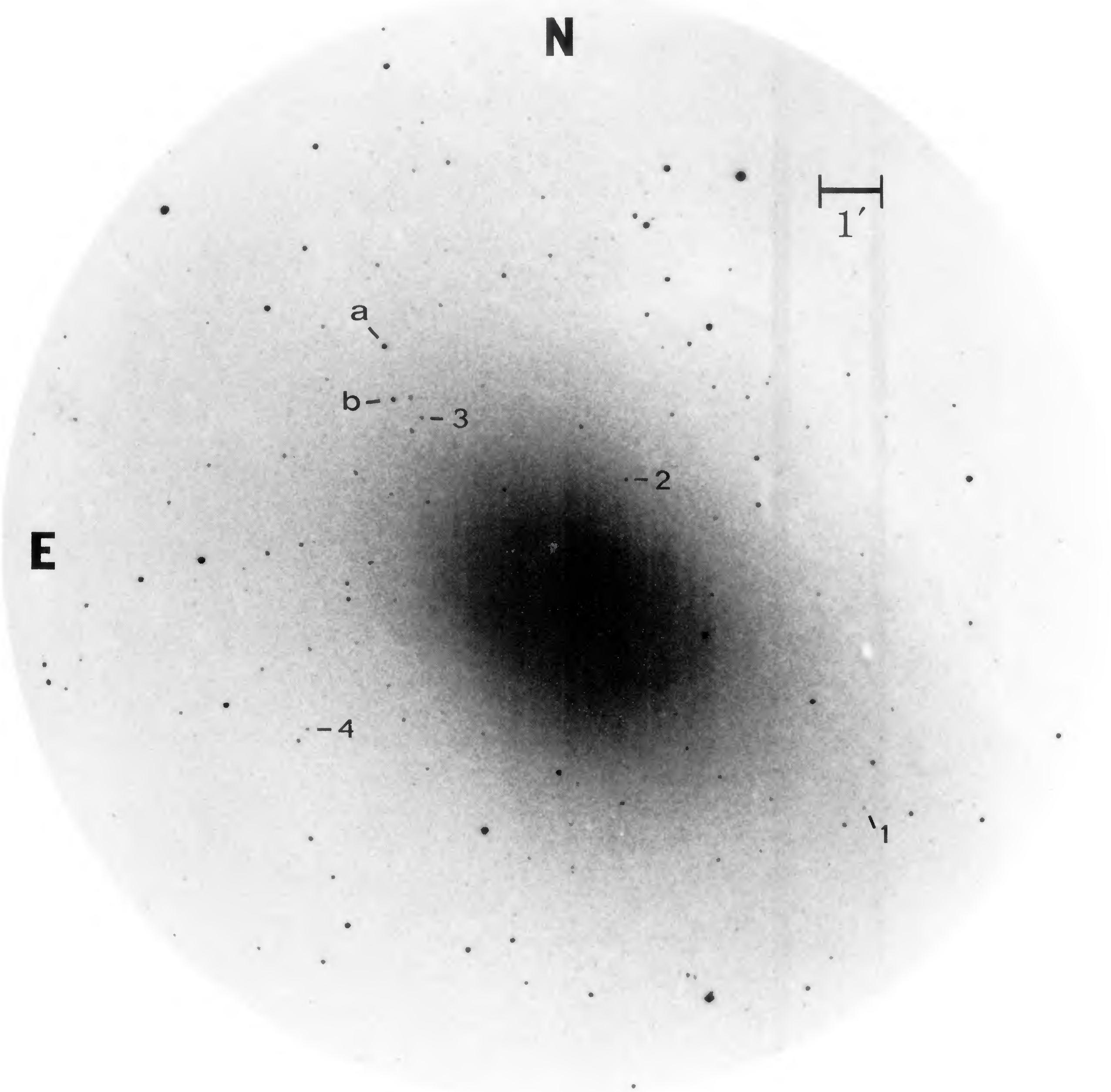

6563 / 27

FIG. 1*a*

FIG. 1.—(*a*), (*b*) A pair of on-line off-line image tube photographs of the nucleus of M31. The on-line plate isolates Hα with the interference filter λ_c 6563 Å (27 Å FWHM). The off-line plate samples λ_c 6204 Å (150 Å FWHM). The four novae are marked with arabic numerals. The letters *a* and *b* refer to field stars used for plate calibration.

CIARDULLO *et al.* (*see* page 93)

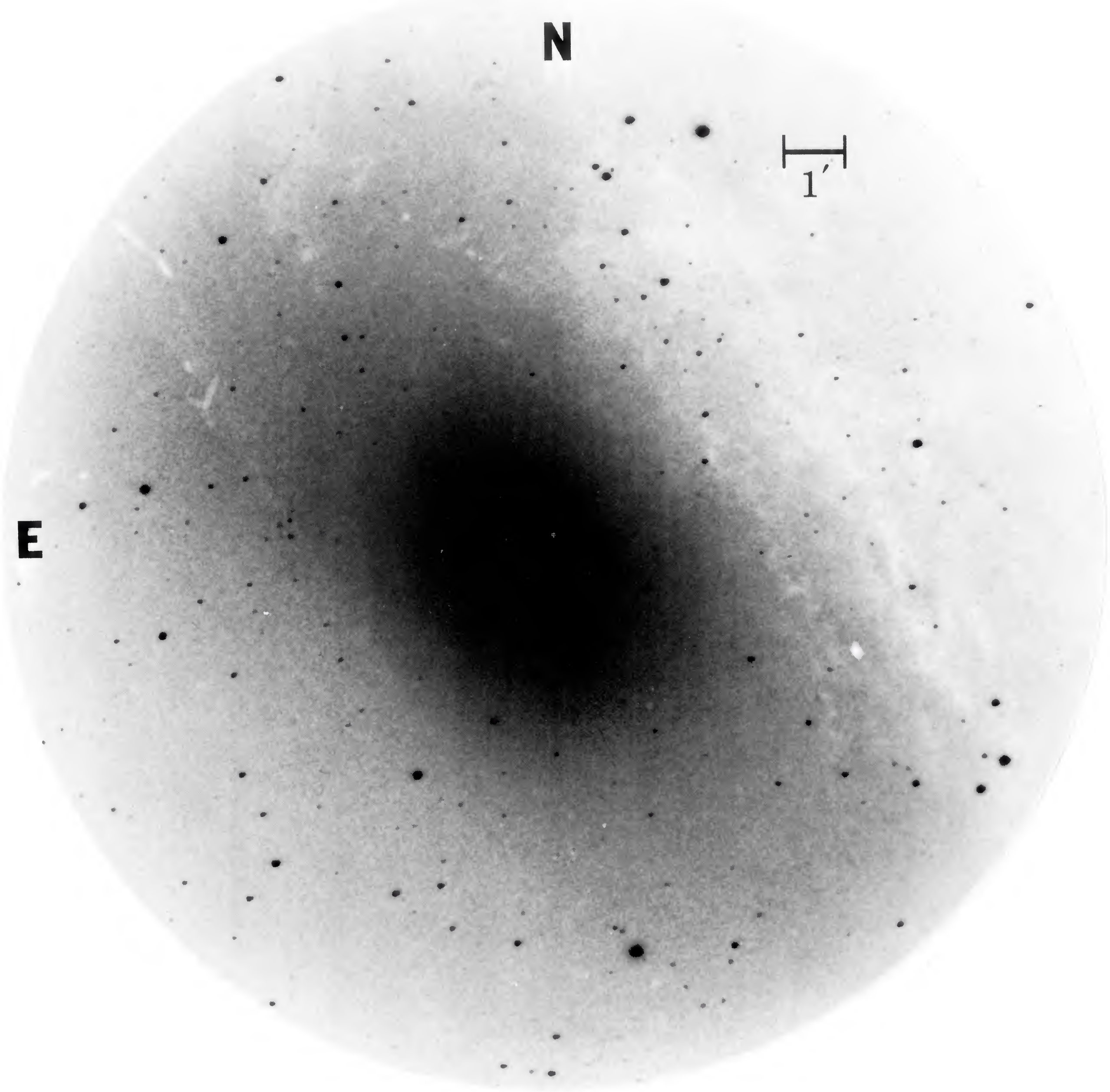

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FIG. 1*b*

CIARDULLO *et al.* (*see* page 93)