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DISCOVERY OF THE REMNANT OF S ANDROMEDAE (SN 1885) IN M31

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ABSTRACT

We have discovered the long sought after remnant of the celebrated 1885 supernova, commonly known as S Andromedae, which occurred in the nuclear bulge of M31. Optical CCD images of M31's nuclear bulge taken with a narrow-passband filter centered on the Fe I resonance line at 3860 Å show an unresolved spot of obscuration located within 1″ of SN 1885's reported position. The absorption feature does not show on images taken using a broader filter centered farther to the blue at 3476 Å, nor does it correspond to any previously reported dust cloud in M31's nuclear region. Our detection of SN 1885's remnant in Fe I absorption suggests that (1) the remnant contains appreciable iron-rich ejecta, consistent with a Type I classification; (2) the ejecta are still largely cold and freely expanding; (3) S And's Fe I absorption-line profiles must be quite broad, ~125 Å; and (4) S And probably occurred on the side of M31's bulge nearer to us. Future absorption-line observations of S And have the potential of becoming among the most informative observations ever taken of a Type I supernova.

Subject headings: galaxies: individual (M31) — galaxies: nuclei — stars: supernovae

I. INTRODUCTION

The famous historical supernova (SN) reported in 1885 August in the nuclear bulge of M31, commonly known as S Andromedae, is the second brightest supernova observed in modern times ($v_{max} = 5.8$), the brightest Type I SN observed over the last 400 yr, and the first ever reported extragalactic supernova. S And played a historic role in efforts to gauge the scale of the universe, being used by both Curtis and Shapley in their 1920 "Island Universe" debate.

S And's reported spectrum showed no hydrogen lines, which defines it as Type I, but the supernova appears to have differed somewhat from the classic Type Ia SN (see review by de Vaucouleurs and Corwin 1985, hereafter dVC; Graham 1988; Chevalier and Plait 1988). Despite good agreement between many of S And's prominent spectral features and those of typical SN Ia, S And lacked the strong Si II 6150 Å feature which is often regarded as characteristic of SN Ia (dVC). S And was orange near maximum light, while standard SN Ia are white. S And's light curve was peculiarly fast compared to most SN Ia, although fast light curves have been observed for some SN Ia (e.g., SN 1939B; dVC). SN 1885's historically recorded position, just 16″ from the center of the nucleus of M31 (dVC), suggests an old stellar population progenitor, consistent with a Type Ia classification.

Currently favored models of Type Ia SNe involve the deflagration or detonation explosion of an accreting white dwarf, which is converted largely to iron in the event. Chevalier and Plait (1988) suggest that the peculiar properties of SN 1885 might be explained by a modification of the standard SN Ia model, in which SN 1885 ejected only part of its envelope, leaving behind a white dwarf or neutron star remnant.

Previous searches for the remnant of SN 1885 in the optical (Jacoby, Ford, and Ciardullo 1985; dVC), in the radio (Pooley and Kenderdine 1967; de Bruyn 1973; Spencer and Burke 1973; Dickel and D'Odorico 1984), and in X-rays (van Speybroeck and Bechtold 1981) have all failed. In this *Letter*, we present optical images which reveal S And's remnant for the first time. Our observations are described in § II, with the results given in § III and discussed in § IV.

II. OBSERVATIONS

Despite continued emphasis on detecting S And's remnant through optical line emission (Chevalier and Plait 1988), previous attempts to detect the remnant of S And in the optical have proven unsuccessful. This is attributable in part to M31's great brightness at S And's position (16″ from the nucleus), and in part to the intrinsic faintness of the remnant in emission. On the other hand, the bulge's brightness could be put to advantage to detect the remnant in absorption rather than emission. If S And occurred on the near side of M31's bulge, then its remnant might produce an observable patch of obscuration silhouetted against M31's bright nuclear region. A similar absorption technique has been successfully employed to study the remnant of SN 1006. In that case, the background source was a single faint sdOB star (Schweizer and Middleditch 1980) fortuitously positioned behind and close to the projected center of the remnant (Wu *et al.* 1983; Fesen *et al.* 1988).

Since S And was a Type I event, most of its ejecta is expected to be iron-rich. Following our work on SN 1006 (Hamilton and Fesen 1988), it became evident that most of the iron in SN 1885 was likely to be in the neutral and singly ionized phases, Fe I and Fe II. The expansion velocities predicted by defla-

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gration and detonation models of SN I (Woosley and Weaver 1987; Woosley, Taam, and Weaver 1986) suggested that absorption-line profiles might be of order 200 Å wide. It was in the light of these considerations that we chose to observe S And using a 200 Å wide on-band filter effectively centered at the Fe I 3860 Å resonance line, and a 500 Å wide off-band filter somewhat farther into the blue, where confusing dust lanes should be plainly visible.

Optical images of M31's central bulge were obtained on 1988 November 9 and 10 (UT) using an 800 × 800 pixel Texas Instruments CCD at the prime focus of the 4 m telescope at Kitt Peak National Observatory. The system produces a field of view which is 3'.9 square, with a pixel size of 0''.30. Images were obtained using two filters which effectively gave "on" and "off" Fe I absorption images. The on-band filter was a narrow passband interference filter ($\lambda_c = 3908$ Å; FWHM = 193 Å) which covered the Fe I resonance line at 3860 Å. The off-band filter had a wider passband ($\lambda_c = 3476$ Å; FWHM = 488 Å) and was centered more to the blue, so as to enhance the visibility of the conventional dust lanes in M31. The off-band filter also has a 0.3% red leak between 6800 and 7300 Å. The telescope's prime focus f/2.7 ratio produces a passband shift of 10–15 Å to the blue for both filters (E. Carder, private communication). In the case of the on-band filter, this centroid shift, combined with the 3908 filter's transmission profile which is asymmetrically peaked toward the blue, yielded a filter transmission curve that is nearly centered on the Fe I 3860 Å line.

The images were obtained in a drift scanning mode in which the image is allowed to drift slowly while the CCD is moved synchronously on a precise stage by single pixel increments, so that the same part of the image falls on the same charge packet. In order to keep count rates for M31's stellar-like nucleus within acceptable limits, the telescope's aperture cover was partially closed during the exposures. Integration times were 640 s for both the 3476 and 3908 filters. Image data reduction included bias subtraction and dome flat-field corrections.

The images presented in Figure 1 (Plate L3) were constructed from two on-band and one off-band exposures taken on the second night, when the seeing was excellent, the FWHMs of star images being 0''.95 ± 0''.1.

III. RESULTS

Figure 1 shows our Fe I on-band 3908 and off-band 3476 filter images of the bulge of M31. Numerous absorbing dust lanes threading the bulge are evident in both on-band and off-band images. At the position of S And, however, there is an unresolved spot of obscuration which is present only in the Fe I on-band 3908 filter image, not in the off-band image. The detected feature is present on three separate 3908 filter images taken over two nights. The size of the absorption feature equals the stellar seeing disk in all three images. In the two images taken under the better seeing conditions on the second night, the feature amounts to about a 10% maximum depression in the bulge's brightness. The spot's position at 15''.2 ± 0''.3 west and 4''.1 ± 0''.3 south of M31's optical center is in excellent agreement with S And's historically reported position of 15''.4 ± 0''.1 west and 3''.95 ± 0''.1 south from the center of M31 (as determined by dVC).[2] The spot of obscuration does not correspond to any of the known dust clouds in M31's nuclear region (Johnson and Hanna 1972; Hodge 1980; Kent 1985; dVC), and indeed the off-band image in Figure 1 shows no obvious contamination by dust at the position of the spot. The spot at the position of S And appears to be the only absorption feature near M31's central bulge that was detected exclusively in the on-band filter image.

Figure 2 (Plate L4) shows a ratio image where the Fe I on-band 3908 filter image has been divided by the off-band 3476 filter image. The ratio image highlights differences between the two images while decreasing both the luminosity gradient of the bulge and the visibility of ordinary dust features. The absorption spot at the position of S And shows up prominently in this image. Indeed, it is the most extreme 3908/3476 colored object relative to the average 3908/3476 color of M31's bulge at a given radius. Note that the dust lanes, instead of appearing reddish, actually appear slightly blue in the ratio image. This is because the 3476 filter has a small red leak at around 7000 Å where the bulge is quite bright.

The peak absorption contrast of 10% observed at the position of S And in the on-band 3908 filter image will have been reduced by the 1'' seeing, by light entering in the wings of the on-band filter, and by any bulge stars in front of S And. The observed 10% contrast can be used to deduce a minimum diameter of the expanding ball of absorbing Fe I. The minimum diameter occurs if S And lies entirely on this side of the M31's bulge. If S And were located somewhere in the middle of the bulge, then the Fe I diameter would have to be larger to produce the same observed 10% contrast. Taking into account the 3908 filter transmission profile, we find that the minimum diameter is equivalent to an Fe I absorption line full width of about 125 Å, corresponding to an expansion velocity of ± 5000 km s^{-1}. At the distance of M31 (distance modulus 24.1; dVC), this would imply an apparent image diameter of 0''.33, consistent with the unresolved nature of the absorption image of S And at 1'' seeing.

On the other hand, the absence of detectable absorption in the off-band 3476 filter image places certain upper limits on the possible size of the absorbing Fe I sphere. This is because the 3476 filter encompasses the Fe I resonance line at 3441 Å and also overlaps the strong Fe I 3720 Å resonance line at the red edge of the filter. If Fe I absorption were extremely broad it would have been detectable with the off-band filter. The combination of the 3476 filter transmission profile (including its red leak) with the spectrum of the background starlight from the bulge, which falls off toward the blue, indicates that the Fe I cannot be much broader than 125 Å.

We therefore conclude that the maximum expansion velocity of the absorbing Fe I sphere in S And must be close to 125 Å full width ($= \pm 5000$ km s^{-1}), and that S And probably lies on the side of the bulge nearer to us.

IV. DISCUSSION

The fact that S And contains an appreciable quantity of Fe I puts an upper limit of about 10^{35} ergs s^{-1} on the photoionizing luminosity of any UV or X-ray source, such as a white dwarf or neutron star, at the center of S And. Such a source would have ionized all the Fe I in S And over its 100 yr age. In the absence of a central source of photoionization, the remnant of a Type I supernova is expected to have recombined largely into the neutral phase at a few years old, when heating and ionization by radioactive energy input has become negligible (Meyerott 1980). Because S And has not yet collided with much ambient medium, UV and X-ray emission from hot shocked

[2] In the finding chart given as Fig. 2 of dVC, S And's position is incorrectly placed 2''–3'' too far to the west.

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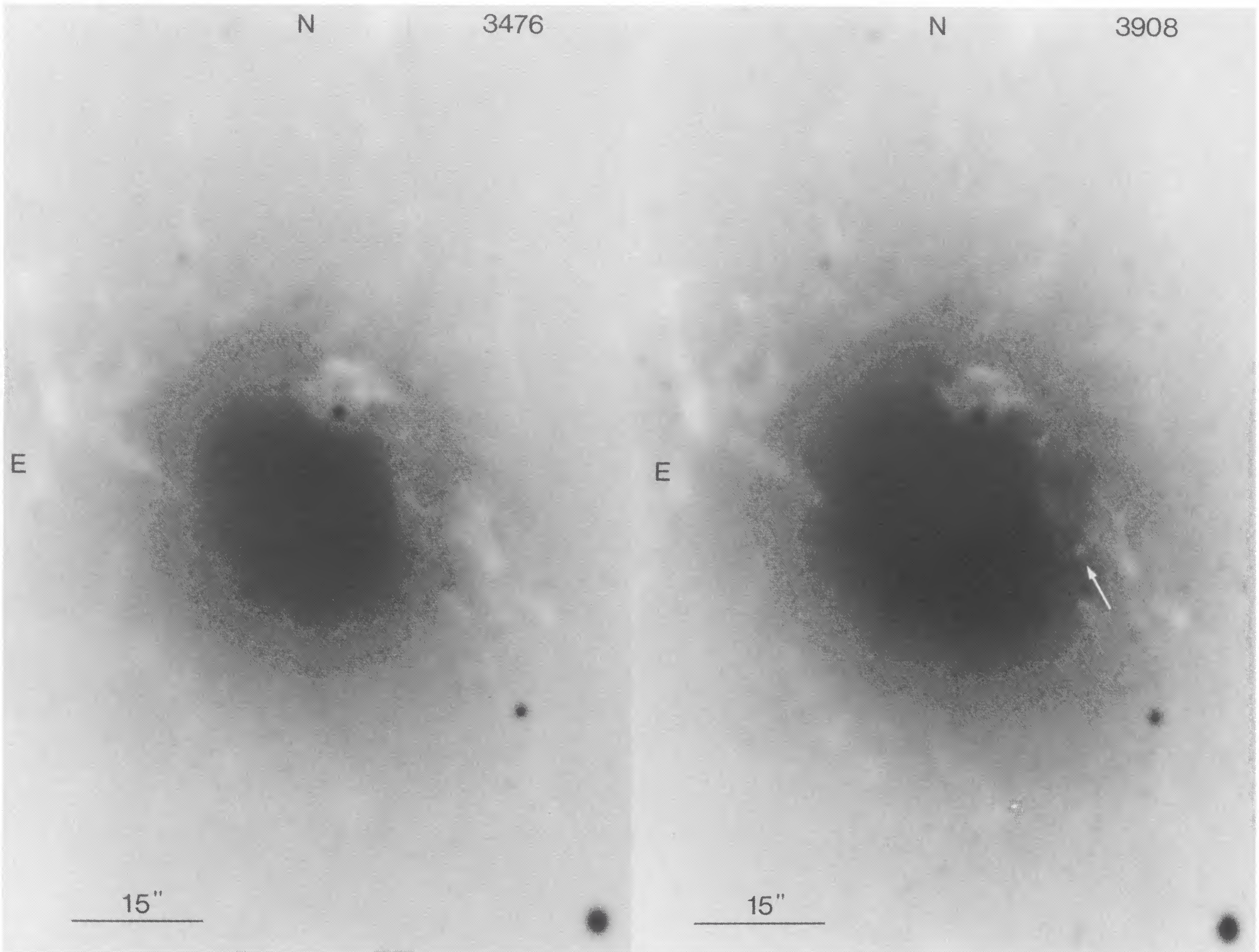

FIG. 1.—Optical images of M31's nuclear bulge. Right image, taken with a 3908 interference-filter (FWHM = 193 Å) effectively centered on the Fe I resonance line at 3860 Å, shows an unresolved spot of obscuration (*arrow*) coincident with S And's historically reported position. This obscuration spot is not detected on the left image, taken with a 3476 filter (FWHM = 488 Å).

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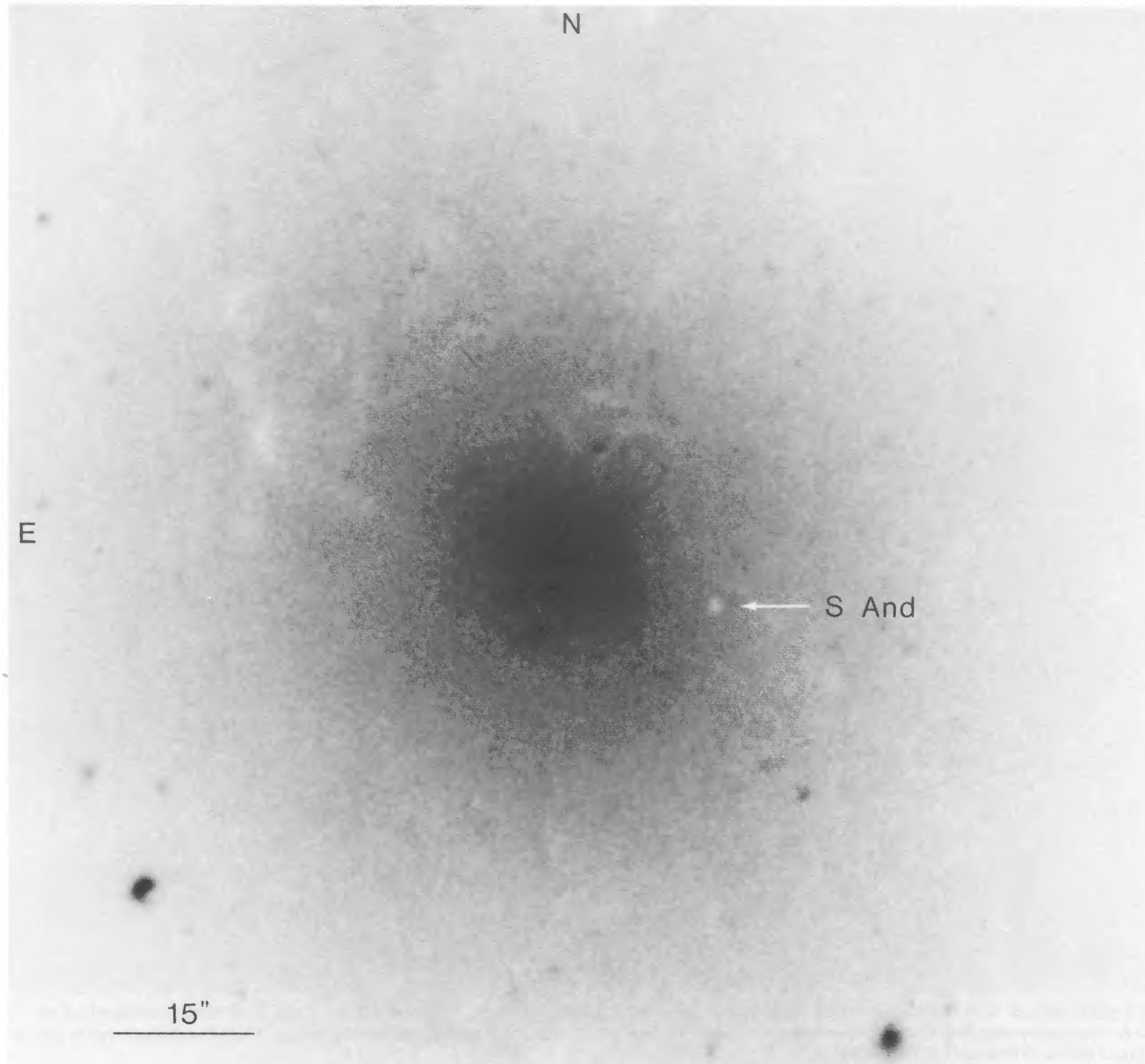

FIG. 2.—Fe I on-band 3908 filter image divided by the off-band 3476 filter image. This ratio image suppresses stellar and conventional dust features common to both images, thereby enhancing the visibility of S And's Fe I rich remnant (*arrow*).

FESEN, HAMILTON, AND SAKEN (*see* **341**, L56) ejecta is still too weak to have had any appreciable effect in photoionizing unshocked ejecta (Hamilton and Fesen 1988). Recombination can be ignored because the recombination time exceeds the age of the remnant after it is 4 yr old.

In S And, the main source of photoionizing radiation is starlight from the bulge of M31. We estimate the lifetime of Fe I in SN 1885 exposed to the light from M31's bulge to be just 5 yr; however, the optically thick inner parts of ejecta should be shielded, and thus remain neutral. It follows that S And's remnant should be mainly Fe I in the inner parts of the iron-rich ejecta, and mainly Fe II in the outer parts. As it happens, S And should be undergoing a particularly rapid phase of evolution at its present age of about 100 yr old, because the expanding core is beginning to become optically thin to photoionizing radiation (Hamilton and Fesen 1988). At the present time an Fe I to Fe II ionization front should be moving rapidly (at about 10,000 km s^{-1}) inward into the ejecta. This is consistent with the conclusion in § III that the diameter of the absorbing Fe I sphere in S And is of order ± 5000 km s^{-1}, significantly less than the radial extent of iron predicted by either deflagration or detonation models of SN I. We expect that iron outside ± 5000 km s^{-1} should be largely Fe II. Absorption observations in the UV will be necessary to detect the Fe II, as well as other ions which may be expected to be abundant in S And, such as C II, O I, Si II, and S II.

Because the flux of photoionizing starlight is strongest on the side of S And facing the center of M31, S And is currently getting a one-sided tan. The Fe I to Fe II photoionization front should have penetrated further into the ejecta on the side facing the center of M31. If S And is on the nearer side of the bulge, this asymmetry should show up as a blueshift of the Fe I absorption line profiles. Observation of such a blueshift would provide a clue to S And's location within the bulge along the line of sight.

Observations of S And in absorption have the potential of becoming among the most informative observations ever taken of a Type I supernova. From observed absorption-line profiles, it is possible in principle to determine directly its density and composition as a function of radius in the freely expanding ejecta. S And is at the ideal age, ~ 100 yr, for absorption-line studies. At such an age, the supernova ejecta have not yet been modified appreciably by interaction with the ambient medium, so that it is still possible to observe the ejecta in a pristine state. At 100 yr old, the expected column density through S And, which is decreasing with time t as t^{-2}, is such that weak resonance lines of abundant ions are becoming optically thin, while strong resonance lines are still optically thick. At the same time, S And is old enough and nearby enough that it subtends an image large enough to be observable in absorption. S And's age, coupled with its fortunate positioning apparently to the near side of a dust-free, star-rich field, combine to make S And an exceptionally favorable target for future absorption observations. However, the full potential of absorption studies of S And will be realized only when S And is observed with the 0."1 resolution of the Hubble Space Telescope.

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