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FAINT OBJECT CAMERA OBSERVATIONS OF A GLOBULAR CLUSTER NOVA FIELD

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ABSTRACT

The Faint Object Camera onboard *Hubble Space Telescope* has obtained *U* and *B* images of the field of Nova Ophiuchi 1938 in the globular cluster M14 (NGC 6402). The candidate for the quiescent nova suggested by Shara et al. is clearly resolved into at least six separate images, probably all stellar, in a region of ~0″.5. Although two of these objects are intriguing as they are somewhat ultraviolet, the actual nova counterpart remains ambiguous, as none of the images in the field has a marked UV excess. Many stars within the 1″.4 (2 σ) uncertainty of the nova outburst position are viable counterparts if only astrometric criteria are used for selection. The 11″ × 11″ frames easily resolve several hundred stars in modest exposures, implying that *HST* even in its current optical configuration will be unique for studies of very crowded fields at moderate ($B \sim 22$) limiting magnitudes.

Subject headings: clusters: globular — stars: novae

1. INTRODUCTION

Only two novae are known to have occurred in globular clusters. T Sco was seen very near the center of M80 (NGC 6093) in 1860, before the application of photography to astronomy, and so was studied only visually (Luther 1860; Pogson 1860). However, in 1938, a 16th mag variable appeared in M14 (NGC 6402) and was recorded on multiple plates (Hogg & Wehlau 1964). Since the variable has not been seen in the bright state before or after that year, despite intensive observations of the cluster, this object was almost certainly a classical nova.

Recovery of the quiescent Nova Oph 1938 would be important for a variety of reasons. Close binary stars are thought to dominate the dynamics of globular clusters (Elson, Hut, & Inagaki 1987), yet only a handful of short-period binaries are known in clusters (Margon 1990): one dwarf nova is known in each of M5 (Margon, Downes, & Gunn 1981) and M30 (Margon & Downes 1983), and eclipsing blue stragglers are found in two globular clusters (Margon & Cannon 1989; Mateo et al. 1990). Although a number of binary radio pulsars have very recently been identified in clusters, and they may in fact be rather common (Kulkarni, Narayan, & Romani 1990), those systems seem unlikely to be amenable to optical or ultraviolet spectroscopy. Quiescent novae generally show strong emission lines, raising the possibility of determination of He and heavy element abundances independently from past techniques applied to globular clusters.

Substantial progress has been made on the problem of recovery of the M14 nova by Shara et al. (1986) and Shara, Moffat, & Potter (1990, hereafter S1 and S2, respectively). Using multicolor CCD photometry, S1 have called attention to a faint ($B \sim 20.2$) candidate at a position compatible with that which they measure for the nova at maximum from the 1938 discovery plates. Their photometry indicates an ultraviolet excess for this object, $(U-B)_0 = -0.3 \pm 0.4$, and based upon this color and the positional agreement, they suggest this object is the quiescent nova. Subsequently, S2 have obtained further imagery and a spectrum of the faint object. Although ground-based observations in this very crowded field (about one core radius from the cluster center) are extremely difficult, S2 conclude that the candidate image is extended, and that the spectrum weakly shows Hα in emission; a red continuum is attributed to contamination by one or more unrelated stars inferred in the spectrograph slit.

2. OBSERVATIONS

Brief CCD exposures of the field kindly provided by H. Ford were used to perform astrometry on the quiescent nova candidate; an example of these data is shown in Figure 1*a* (Plate L21). Measures were made of a variety of anonymous secondary standard stars that appear both on the CCD frames and also in the *HST* Guide Star Selection System digital data base, and the GSSS software was then used to derive an accurate position for the S1 quiescent nova candidate. The residuals of the fitting process indicate our CCD position is accurate to ±0″.5 in each axis. However, our position so derived is in very poor agreement with the astrometric result for the nova at maximum quoted by S1: their stated absolute errors are ±1″ in each coordinate, but the two results differ by ~6″. As the field of view of the *HST* Faint Object Camera in the f/96 mode is only 11″, this discrepancy is cause for concern.

By examining GSSS positions for nearby SAO stars, it has been straightforward to ascertain that approximately 2″ of the

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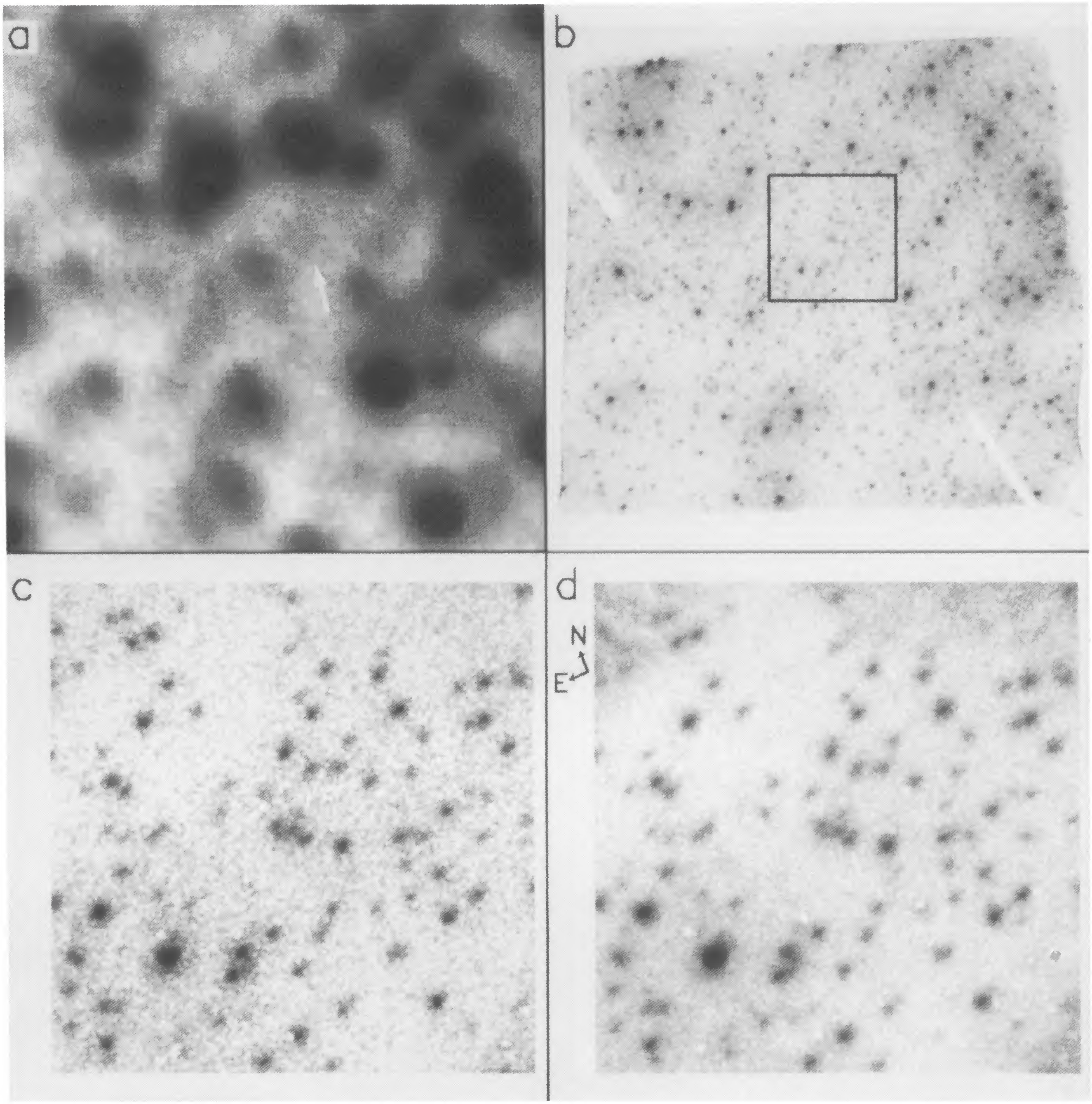

FIG. 1.—The field of Nova Oph 1938 in the globular cluster M14. Images of the nova at outburst, as well deep ground-based images of the field in quiescence, may be found in S1. (*a*) The field as observed in a 200 Å band centered at 5250 Å using the 4 m reflector of the Cerro Tololo Inter-American Observatory and TI CCD detector; the pixel size is 0″.29, and the frame measures ~25″ on each side. Note the somewhat peculiar cardinal orientation of this and all other frames on the figure. This brief (20 s) exposure obtained in typical seeing (measured images 1″.5 FWHM) is provided for comparison of angular resolution (but of course *not* sensitivity) with the FOC data. Although we do not expect it to be prominent on this published reproduction, the $B \sim 20.2$ quiescent nova candidate suggested by S1 (*arrow*) is clearly visible in the CCD data. (*b*) The *HST* Faint Object Camera acquisition image of the same field, a 600 s exposure in the F342W filter. The orientation and scale are identical to panel (*a*). Note the large number of ground-based images which are here multiply resolved and the "nebulosity" near brighter ($B \lesssim 19$) objects caused by the extended point-spread function. The square box is a 5″ × 5″ field centered near the position of the nova outburst and demarcates the area covered by the lower panels of this figure. (*c*) A 2500 s ultraviolet (F342W) FOC exposure of the central 5″ × 5″ of the nova field. Note the very large number of stars clearly resolved in this small field. The pixel size is 0″.02, and the somewhat distorted image shapes are due to less than optimal guiding with the spacecraft in coarse lock. The candidate suggested by S1 resolves into the "clump" of stars in the center of the frame, plus the one object slightly to the SW. Isophotal traces of an enlargement of this region are shown in Fig. 2. Note, however, that many other stars visible on this frame are compatible with the position of the nova at maximum light. (*d*) Same as (*c*), but in a blue (F430W) filter. Note the absence of any object of conspicuously peculiar color near the center of the frames.

difference between our result and that of S1 is due to systematic differences in either the local or global reference frames: S1 employed only those nearby SAO stars (as the GSSS was then not available), while the astrometric basis of the *HST* Guide Star Catalog (GSC) is more complex (Russell et al. 1990). However, the origin of the remaining 4″ is still unclear. H. S. Hogg has kindly loaned the best of the 1938 maximum light plates to M. Shara for remeasurement, using a PDS and the GSSS software; the latter has communicated a new position for the nova at maximum which agrees very well with our CCD measures of the S1 candidate, thus removing the discrepancy. The internal errors of our measures and the remeasurement of the maximum light plate ($\pm 0\farcs5$ in each coordinate) are similar, but presumably the latter position is preferred as it places no presupposition on the identification of the quiescent object. We therefore adopt that maximum light position henceforth, viz.,

$$\alpha(1950) = 17^{h}35^{m}00\fs75 \; , \quad \delta = -03^{\circ}12'58\farcs45 \; ,$$

where this position is in the frame of the *HST* GSC; this latter qualification is significant because the GSC frame is known to differ somewhat from other astrometric systems.

We stress that although the position quoted in S1 is in error and should be disregarded in favor of the above data, this problem with that earlier paper is essentially a curiosity and in no way affects the conclusions of S1, insofar as we can determine. In particular, the agreement of our minimum light CCD image position with that now redetermined for the nova at maximum implies that the faint candidate suggested by S1 is indeed viable on positional grounds.

We obtained *Hubble Space Telescope* images of the Nova Oph 1938 field in 1990 August, as part of the early science assessment observations, using the Faint Object Camera (FOC) in the f/96 mode, which provides $0\farcs02$ pixels covering a small ($11'' \times 11''$) field, as well as a $22'' \times 22''$ field acquisition mode. Operational requirements dictated that the observations were made with the spacecraft in coarse rather than fine lock, a less than optimal configuration, as $\sim 0\farcs02$ guiding excursions are expected and were indeed encountered, significantly degrading image quality. Gaussian fits to the core of the images typically exhibit widths of $0\farcs08$ FWHM, although the extended image wings are obviously non-Gaussian. A 600 s exposure, obtained for field acquisition in the F342W (ultraviolet) filter, is shown in Figure 1*b*. By ground-based standards, a remarkably large number of stars are resolved in this very small field: our automated photometry programs (described below) easily identify more than 500 discrete objects. Real-time identification with *HST* of crowded fields using ground-based finding charts is complex, as comparison of Figures 1*a* and 1*b*, which are the same scale and region, readily illustrates.

The FOC images show marked variation in sky density across the small frames, clearly a manifestation of the extended point-spread function (PSF) of the optics and the crowding in the field. Despite these cosmetic oddities, even the brief acquisition image reaches a moderately faint limiting magnitude, $m_{\mathrm{F342W}} \sim 22$, without approaching confusion, and numerous images which appear single on the ground-based data are easily resolved into multiple objects.

Upon verification of the spacecraft pointing, F342W and F430W exposures of the field of 2500 s duration each were obtained; each exposure was subdivided into two 1250 s segments. These ultraviolet and blue bandpasses have significant differences from the Johnson systems, but we use the *U* and *B* notation henceforth for convenience. These filters were chosen to suppress background red starlight, because most old novae have UV excesses, and because the S1 candidate is reported to have such an excess.

3. ANALYSIS AND DISCUSSION

After flat-fielding and correction for geometric distortion, comparison of the bright image cores on the four long-exposure frames reveals somewhat noncircular images, with the nature of the distortion slightly different on each frame. These difficulties are due largely to guiding in coarse rather than fine lock, and also the limited signal-to-noise ratio of the data. The on-orbit photometricity of the FOC remains to be determined, our data have no ready absolute photometric calibration in any case, and the F342W and F430W bands are known to differ substantially from the Johnson systems; these factors combine with the less-than-optimal image shapes to make us extremely cautious about attempting to extract photometric information at this time. Nonetheless, certain preliminary conclusions seem warranted.

Small ($5'' \times 5''$) regions of the sum of each of the two *U* and *B* exposures centered near the location of the nova at maximum are shown in Figures 1*c* and 1*d*, respectively. The faint candidate proposed by S1 is seen to be resolved into at least five distinct images in a region of $\sim 0\farcs35$, hereafter called "the clump," plus a sixth, somewhat brighter image $\sim 0\farcs5$ southwest of the centroid of the clump. In Figure 2 we show an

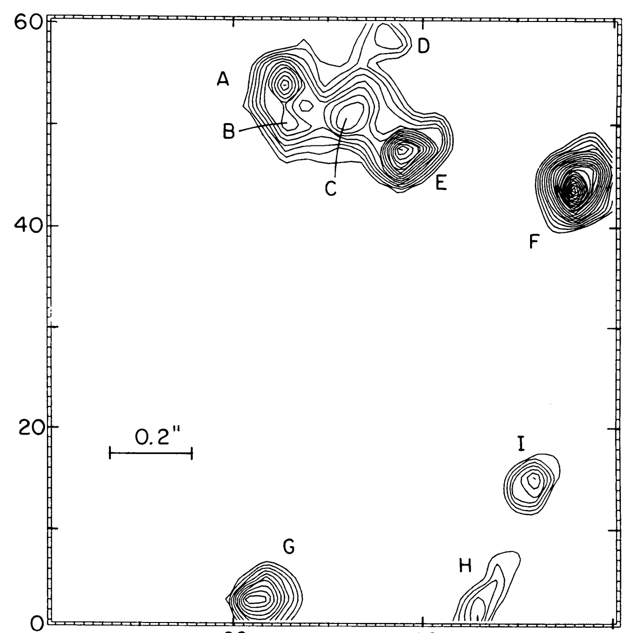

FIG. 2.—Isophotal plot of the central portion of Fig. 1*c*, where the axis units are $0\farcs02$ FOC pixels, the cardinal orientation of that figure is maintained, and the data have been smoothed with a 2×2 pixel box. The contours are linear, and range from 20 through 80 total counts per pixel in steps of 2 counts. A typical background in this region is ~ 12 counts. The panel is centered approximately at the astrometrically derived position for the nova at maximum; the box is sized to delimit the $\pm 1\ \sigma$ uncertainty in this position. At $\pm 2\ \sigma$, about two dozen stars would be included. Stars which we infer may be included in the image of ground-based candidate of S1 are labeled A–F; A–E are referred to as the "clump" in the text. Image H, a composite of at least two objects, is fainter than the limit of our photometry but appears ultraviolet in a comparison of Figs. 1*c* and 1*d*, and may therefore be worthy of further study.

isophotal diagram of this central portion of the FOC field, with objects labeled for ease of future reference. Transfer of our astrometric solution from our CCD data to the FOC frame has been accomplished with sufficient secondary standards that positions of the FOC pixels are known in the GSSS system to an accuracy of ~0."25. Because the nova maximum light position has additional uncertainty of ±0."67, this position is known on the FOC frames to ±0."71. Figure 2 is sized to delimit this ±1 σ uncertainty.

S1 remark that for the distance and reddening of M14, $(m - M) = 16.9$ and $E(B-V) = 0.58$, respectively (Harris & Racine 1979), their $B \sim 20.2$ candidate is ~1.5 mag more luminous than the mean of quiescent novae in the field. Our resolution of the object into many images removes this discrepancy. S2 have concluded that their ground-based CCD data show the candidate's image as elongated; we speculate that our "sixth" image (star F), based both upon its brightness and relatively clean separation from the remainder of the complex field, is the origin of the extension discussed by those authors.

Comparison of the six images A–F near to the maximum light position, plus immediately neighboring images, on the *U* and *B* frames shows no image with obviously peculiar colors. Which, if any, of these objects is the quiescent nova, and what is the source of the marked UV excess reported by S1?

We have created instrumental color-magnitude diagrams for the well-detected stars in the 11" field of the long exposures, using aperture photometry as well as two different programs each designed for automated photometry in crowded fields with panoramic detectors, DAOPHOT (Stetson 1987) and DoPHOT (Mateo & Schechter 1989). In an effort to understand the effect of the complex PSF and poor image shape on the result, we have employed a variety of approaches to specifying the PSF, e.g., fitting analytic functions, empirical tables, and employing the PSF determined by the FOC Instrument Definition Team (IDT) on bright stars. A typical result of these efforts is shown in Figure 3.

Despite the photometric caveats discussed above, and although the colors employed in Figure 3 are somewhat unconventional, there is evidence in this diagram for the main-sequence turnoff. The turnoff is expected at $B \sim 21.5$, thereby providing a rough estimate of the m_{F430W} absolute calibration. The photometry becomes highly incomplete for $m_{F342W} > 23.0$ and $m_{F430W} > 22.5$, where the automated algorithms are unable to locate stars reliably. The lack of objects in the red, faint quadrant of the figure is at least partially simple observational selection: only somewhat blue images are well detected in both bandpasses used and can thus yield a color. The figure also verifies the casual impression gained through comparison of Figures 1*c* and 1*d*: no star near in location to the maximum light nova image has an outstanding UV excess, at least in comparison with ~200 neighbors on the frame. Two of the six resolved objects near the nova outburst position, stars A and E, do lie near the outside of the UV envelope on the figure. These two stars remain in approximately this position in the diagram regardless of which reduction algorithm or PSF we employ. Given our lack of photometric calibration, it is difficult to assess the significance of this fact. At the moment we see no compelling reason to believe that these or any of the neighboring objects on the figure are anything other than normal stars near the main-sequence turnoff, although this conclusion requires confirmation through better photometry.

We of course cannot rule out the possibility that the nova system was fortuitously in eclipse during our *HST* observations, thereby suppressing the UV excess often associated with these systems. This probability is small but not totally negligible. A second effect which could influence the colors of objects in this field as observed from the ground is superposition of multiple images of different intrinsic colors into the seeing disk. Comparison of Figures 1*c* and 1*d* readily shows that star F is quite red [it may, in fact, be responsible for the red spectral continuum discussed by S2, and the unusually red $(B-V)$ found by S1], while we have already noted that stars A and E are more ultraviolet than most other images. We have considered the effect of color dispersion on ground-based photometry by summing our derived FOC magnitudes of individual stars in the clump. This sum would appear on Figure 3 at $m_{F430W} \sim 20$, and ~0.3 mag more ultraviolet than stars of comparable brightness, compatible with both the magnitude and the UV excess reported by S1. Thus the significance of the UV excess inferred from ground-based measurements to the problem of the identification of the nova is unclear.

Finally, we have considered the possibility that our difficulty in unambiguously identifying the quiescent nova counterpart may be because more than one, or even all, of the clump objects we have resolved in our FOC images are associated with the nova, rather than a single stellar image. Although

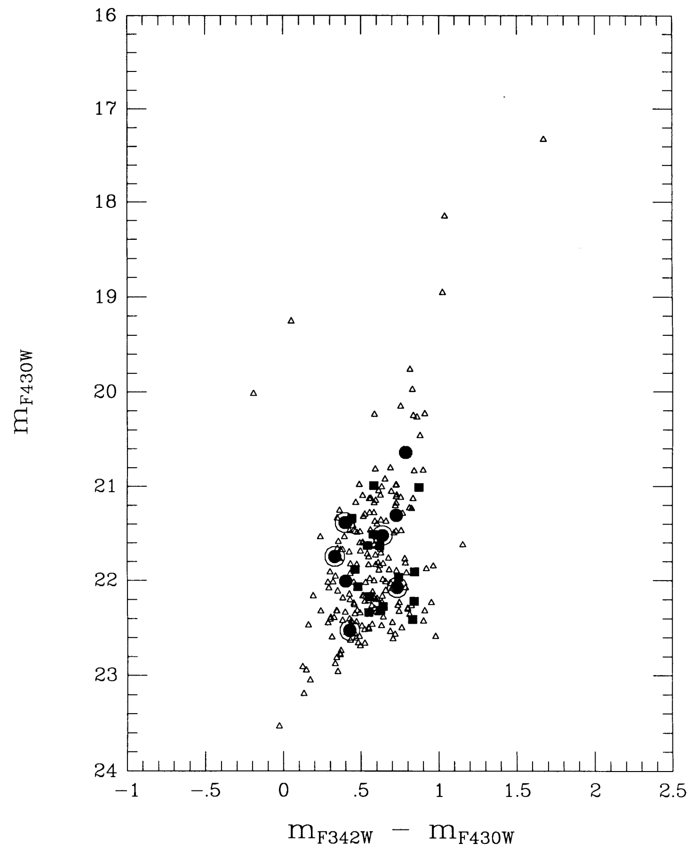

FIG. 3.—An instrumental color-magnitude diagram of objects within the 11" × 11" field of the *U* and *B* FOC images. Instrumental magnitudes are derived using DoPHOT. There is a hint of a main-sequence turnoff, allowing a rough estimate of the m_{F430W} zero-point, as the turnoff is expected at about $B \sim 21.5$. *Filled circles:* objects < 1 σ from the nova outburst position; *filled squares:* objects 1–2 σ from the position. The stars in the "clump" (A–E, Fig. 2) are encircled for emphasis. Only those objects detected on both *U* and *B* frames are displayed here; however, there are no additional candidates with $m_{F342W} < 23.0$ that have UV colors so extreme that they appear only on the *U* frame.

there is no particular reason to suspect that the two events were intrinsically similar other than in age, we must point out that if the extended envelope of Nova Her 1934 associated with DQ Her were moved to the distance of M14, it would measure about $\sim 0\rlap{.}''3$ in angular extent, similar in size to the "clump" we observe. If one or more of the images in the FOC data are in fact knots or similar nova ejecta, it is unclear whether they would call attention to themselves in the peculiar color system of Figure 3, because the strongest spectral feature expected in our bandpasses, [O II] λ3727, lies in both filters. It would be unusual, although not unprecedented, for the knots to be so bright relative to the central star. The DoPHOT best-fit shape parameters do not confidently exclude a nonstellar profile for some of the clump members, but the signal-to-noise ratio of our data is not high (the caption of Fig. 2 provides examples of total counts obtained). We can but remark that it would be an unfortunate coincidence if these knots were of physical size which just eludes the resolution of our observations. We have not yet invested any substantial effort in image restoration or related techniques, which may be of limited value due to the modest signal-to-noise ratio, but we plan to do so. Such techniques, or higher quality narrow-band images centered on typical nebular emission lines, may be helpful in pursuing this issue.

4. CONCLUSION

Observations of the field of Nova Oph 1938 with the *HST* FOC have proven a tremendous advance over previous ground-based data but have also revealed the true difficulty of recovering the quiescent object. Although two stars which are part of the image suggested as a candidate from ground-based data are mildly ultraviolet, and one or the other may be the nova, there is no compelling reason to reject many other nearby candidate objects. It appears that the UV excess reported by S1 from ground-based observations may be due in part or even chiefly to the superposition in their photometry of several stars of different colors, rather than to the presence of any one object with genuinely peculiar intrinsic colors. Our analysis indicates that a similar misleading result would be inferred even if observations with angular resolution of $\sim 0\rlap{.}''3$ were obtained. As S1 have explicitly commented, the most compelling reason to identify their candidate with the nova was the suggestion of a UV excess. If instead only astrometric data are considered in restricting candidates, the FOC images indicate a large number of potential identifications, more than 20 within the 2 σ positional uncertainty of the outburst.

There is no outstanding candidate. Among the half-dozen mildly ultraviolet objects within 2 σ of the nova outburst position and with $m_{\rm F430W} \leq 22.5$, stars A and E in the clump seem the best candidates for follow-up study because, in addition to their color, (1) they are closest to the outburst position; (2) there is a hint of Hα emission from some object near the clump in S2's ground-based spectrum; and (3) there remains the curious but possibly fortuitous coincidence between the size of the clump and that expected for a nova shell.

It seems clear that future progress on this problem is unlikely to come via ground-based observations, even if obtained with extraordinary angular resolution. Further *HST* imagery, however, with either the FOC or WFPC, should be capable of very substantially improving photometry in this field, and these results may reveal a stronger candidate for the nova through either peculiar colors (although not all quiescent novae have UV excesses) or time variability. We also plan to obtain low-resolution spectra of candidates with the *HST* Faint Object Spectrograph.

These preliminary observations clearly indicate the unique value of *HST* imagery in crowded fields at moderate ($B \sim 22$) limiting magnitudes, even given the current optical configuration. As past searches for optical counterparts of interesting objects in many globular clusters (e.g., compact X-ray sources) have relied upon peculiar colors measured from ground-based data in crowded fields during intervals of excellent seeing, our results also presage a strong possibility that further *HST* data will require revision of the proposed counterparts in other clusters.

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