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## OPTICAL DISCOVERY OF AN APPARENT GALACTIC SUPERNOVA REMNANT G159.6+7.3

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### ABSTRACT

Deep  $H\alpha$  images of portions of a faint  $3^\circ \times 4^\circ$   $H\alpha$  shell centered at  $l = 159^\circ.6$ ,  $b = 7^\circ.3$  seen on the Virginia Tech Spectral Line Survey images revealed the presence of several thin emission filaments along its eastern limb. Low-dispersion optical spectra of two of these filaments covering the wavelength range of 4500–7500 Å show narrow  $H\alpha$  line emissions with velocities around  $-170 \pm 30$  km s $^{-1}$ . Both the morphology and spectra of these filaments are consistent with a Balmer-dominated shock interpretation and we propose that these optical filaments indicate that the large  $H\alpha$  emission shell is a previously unrecognized supernova remnant (SNR). *ROSAT* All Sky Survey images indicate the possible presence of extremely faint, diffuse emission from the shell's central region. The shell's location more than  $7^\circ$  off the Galactic plane in a region of relatively low interstellar density may account for the lack of any reported associated non-thermal radio emissions. The rare discovery of a Galactic SNR at optical wavelengths suggests that additional high-latitude SNRs may have escaped radio and X-ray detection.

*Key words:* ISM: supernova remnants – shock waves – X-rays: ISM

### 1. INTRODUCTION

Supernovae (SNe) occupy an important place in astrophysics as they are a primary source of heavy elements in the universe, and generate the creation of neutron stars and cosmic rays. Currently, there are some 275 Galactic supernova remnants (SNRs) recognized (Green 2009) with additional ones identified or discovered every few years (e.g., Brogan et al. 2006).

Before the advent of radio astronomy, only two remnants were known via optical studies: the Crab Nebula associated with SN 1054 and the remnant of Kepler's SN of 1604 (Minkowski 1964). Today, the vast majority of known Galactic SNRs were first identified through their non-thermal radio emissions (Milne 1970; Downes 1971). With increasingly sensitive observations across a broader spectrum of wavelengths, particularly in X-rays via satellites, several recently identified SNRs were discovered through non-radio observations.

The first X-ray discovered Galactic SNR is the radio faint but X-ray bright SNR G156.2+5.7 which was found through *ROSAT* All Sky Survey images (Pfeffermann et al. 1991) and only later confirmed in the radio (Reich et al. 1992). At present, there are more than a dozen SNRs which were discovered through their X-ray emission (e.g., Schwentker 1994; Seward et al. 1995; Busser et al. 1996; Aschenbach 1998; Bamba et al. 2003; Yamaguchi et al. 2004), with dozens more suspected candidate X-ray SNRs (Aschenbach 1999).

Although there are many examples where optical observations have helped identify the SNR nature of suspected radio-detected Galactic SNR candidates (e.g., Parker et al. 2004; Stupar et al. 2007), recent instances where a Galactic SNR is first identified solely through its optical emission are exceedingly rare, with only one case known to the authors. That remnant, G65.3+5.7, was found during a wide-field optical emission-line survey of the Milky Way (Gull et al. 1977). It had been missed in previous Galactic radio SNR surveys due to a weak and partial shell structure (Reich et al. 1979), weak and fragmented associated  $H\alpha$  emission (Sharpless 1959), and was only recognized as an SNR through deep [O III]  $\lambda$ 5007 optical images.

While hundreds of extragalactic SNRs have been first identified through optical imaging (e.g., Mathewson & Clarke 1973; Blair et al. 1981; Matonick & Fesen 1997; Dopita et al. 2010),

the rarity of optically discovered Galactic SNRs is not surprising. Apart from the great sensitivity of Galactic SNR radio and X-ray surveys, only 21% of the 275 known Galactic SNRs have any associated optical emission (Green 2009). Moreover, while early optical investigations of SNRs (Rodgers et al. 1960; van den Bergh et al. 1973, 1978) found relatively bright remnant emissions, recent searches of known remnants typically find only faint or fragmentary optical features detectable only through deep imaging (e.g., Zealey et al. 1979; Mavromatakis et al. 2001; Boumis et al. 2002a, 2002b, 2008; Stupar et al. 2008; Stupar & Parker 2009).

Despite such long odds, here we report the discovery of an apparent new Galactic SNR based on its optical emission properties. It appears as a large, faint shell of emission centered at  $l = 159^\circ.6$ ,  $b = 7^\circ.3$  in the deep but low-resolution  $H\alpha$  emission Virginia Tech Spectral Line Survey (VTSS) of the Galactic plane (Dennison et al. 1998; Finkbeiner 2003). We also show *ROSAT* All Sky Survey images which may indicate the presence of very weak, diffuse X-ray emission from the remnant's interior. Below we present higher resolution  $H\alpha$  images of this shell (hereafter referred to simply as G159) and low-dispersion optical spectra and propose this object is a previously unrecognized Galactic SNR.

### 2. OBSERVATIONS

Narrow passband (FWHM = 30 Å)  $H\alpha$  images of several regions along G159's optical limb were obtained in 2010 February with a backside illuminated 2048 × 2048 SITe CCD detector attached to the McGraw-Hill 1.3 m Telescope at the MDM Observatory (MDM) at Kitt Peak. Typical exposure times were 1000–2000 s. The CCD's 24  $\mu$ m size pixels gave an image scale of 0''.508 and a field of view of approximately 17' square. However, to improve the signal to noise of the detected filament emissions, we employed 2 × 2 pixel on-chip binning. Follow-up, low-dispersion optical spectra of portions of the detected emission filaments were immediately obtained with a Boller & Chivens CCD spectrograph (CCDS) on the Hiltner 2.4 m Telescope at MDM Observatory with a 1''.2 × 5' slit and a 150 lines mm $^{-1}$  4700 Å blaze grating which yielded  $\sim$ 10 Å resolution.

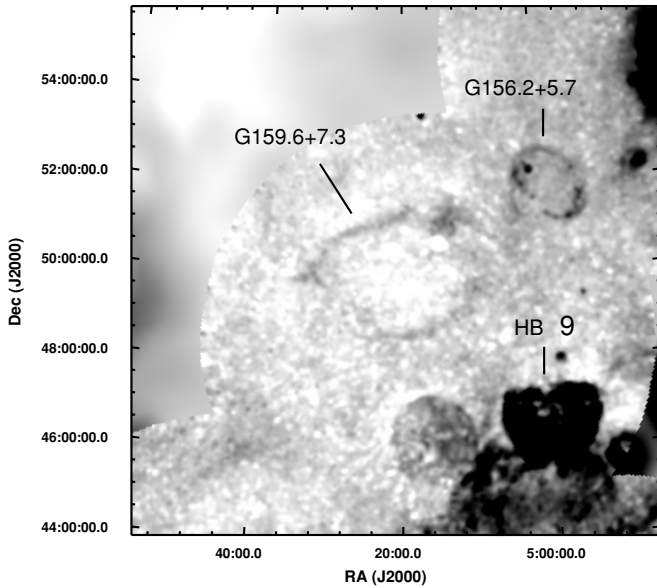


Figure 1.  $H\alpha$  VTSS image of the emission shell G159.6+7.3.

Standard pipeline data reduction of these images and spectra was performed using IRAF/STSDAS.<sup>1</sup> This included debiasing, flat-fielding using twilight sky flats, and dark frame corrections for the images.

### 3. RESULTS AND DISCUSSION

Figure 1 shows the G159 emission shell as it appears on the low angular resolution ( $1.6 \text{ pixel}^{-1}$ ) VTSS of the Galactic plane. The shell is approximately  $3^\circ \times 4^\circ$  in angular size and appears nearly complete except for breaks along its fainter southeastern limb. The shell's  $H\alpha$  flux is extremely weak and is just above the VTSS  $H\alpha$  emission measure limit of  $2 \text{ cm}^{-6} \text{ pc}$  along much of its structure.

Although no filamentary structure is discernible on the VTSS image, our higher resolution  $H\alpha$  images of two regions along the shell's eastern limb (see Figure 2) did reveal several faint filaments. These images (see Figures 3 and 4) show an unresolved overlapping filamentary morphology strikingly similar to that seen in Balmer-dominated filaments found in Galactic SNRs where the SN generated interstellar shocks move through a partially neutral medium (Chevalier & Raymond 1978).

The long curved filament shown in Figure 3 is seen to split up into several thin, fainter, and partially overlapping filaments along either end of the region shown. At these ends, the filamentary emission fades significantly, gradually becoming undetectable even in 2000 s long exposures a few arcminutes away from the region shown. A second, much shorter but more highly curved filament is visible in the lower left-hand side of the image.

The somewhat brighter, N–S aligned filament located in the extreme easterly region of the shell's limb (see Figure 4) also showed multiple and partially overlapping thin filaments; only in this case one also finds considerable surrounding diffuse emission. The nature of this diffuse emission is unclear but

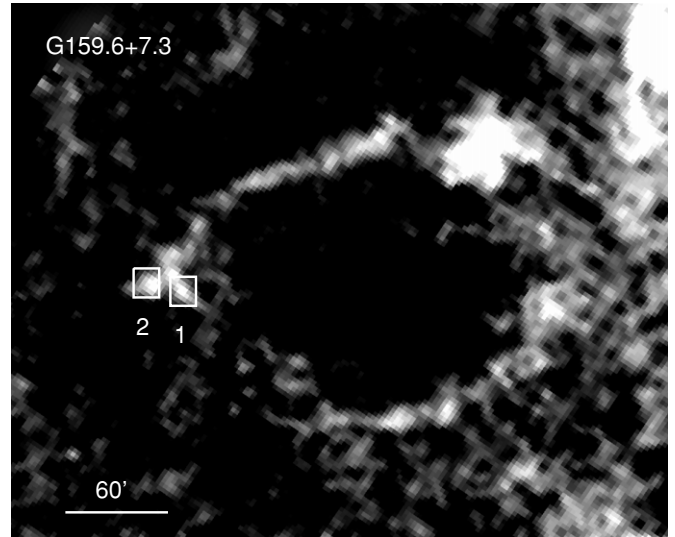


Figure 2.  $H\alpha$  VTSS image showing the two regions where we obtained higher resolution  $H\alpha$  images. North is up; east is to the left.

its location near these filaments suggest a possible connection to the shell. Despite equally deep  $H\alpha$  images taken of several other regions of the shell, including the relatively bright region along the northwestern limb, no similar filamentary emission was detected.

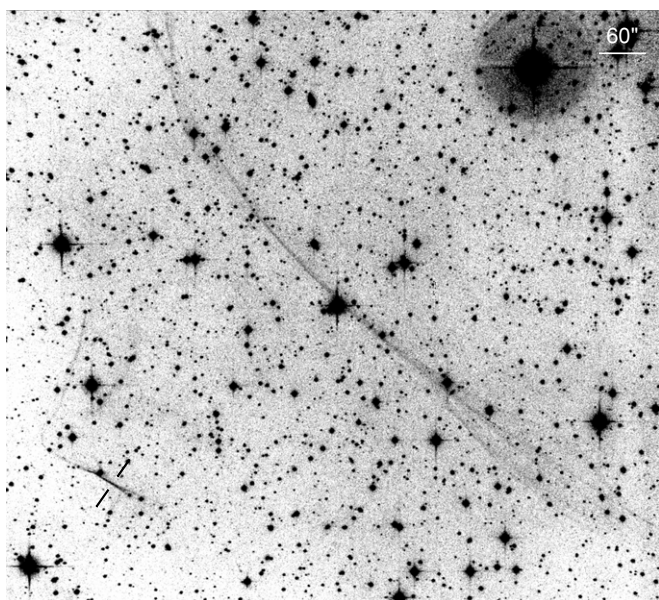
Follow-up, low-dispersion optical spectra of the shell's  $H\alpha$  filaments are consistent with a Balmer-dominated shock interpretation and thus support an SNR identification. In Figure 5, we present our low-dispersion optical spectrum taken of the bright portion of the short filament seen in the southeastern corner of Figure 3. The only emission line seen in its spectrum is that of narrow (unresolved)  $H\alpha$  line emission, with no appreciable [O I]  $\lambda\lambda 6300, 6364$ , [O II]  $\lambda\lambda 7319, 7330$ , [O III]  $\lambda\lambda 4959, 5007$ , [N II]  $\lambda\lambda 6548, 6583$ , or [S II]  $\lambda\lambda 6716, 6731$  emission detected like that commonly present in photoionized gas (e.g., H II regions and planetary nebulae) or optical shock filaments (Fesen et al. 1985). The  $H\alpha$  emission exhibited a blueshift of  $-170 \pm 30 \text{ km s}^{-1}$  and a flux of  $4.6 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ . A marginal detection of  $H\beta$  can be seen in the spectrum suggestive of an  $H\alpha/H\beta$  ratio  $\geq 4$  implying an  $E(B - V) \geq 0.35$ . Such a weak detection of  $H\beta$  emission is consistent with a fairly low amount of extinction of around  $E(B - V) \sim 0.45$  toward G159 suggested from H I measurements taken in this direction and conversions of  $N(\text{H})$  into  $E(B - V)$  values for a typical gas-to-dust ratio (Bohlin et al. 1978; Predehl & Schmitt 1995).

A spectrum was also taken of the roughly N–S aligned filament shown in Figure 4. Again only a weak detection of unresolved  $H\alpha$  emission was seen, with no detectable [N II]  $\lambda\lambda 6548, 6583$  or [S II] emissions despite integrations of up to 1 hr. As before, unresolved  $H\alpha$  emission was seen with roughly the same blueshifted velocity as the other filament, namely,  $-170 \pm 30 \text{ km s}^{-1}$ .

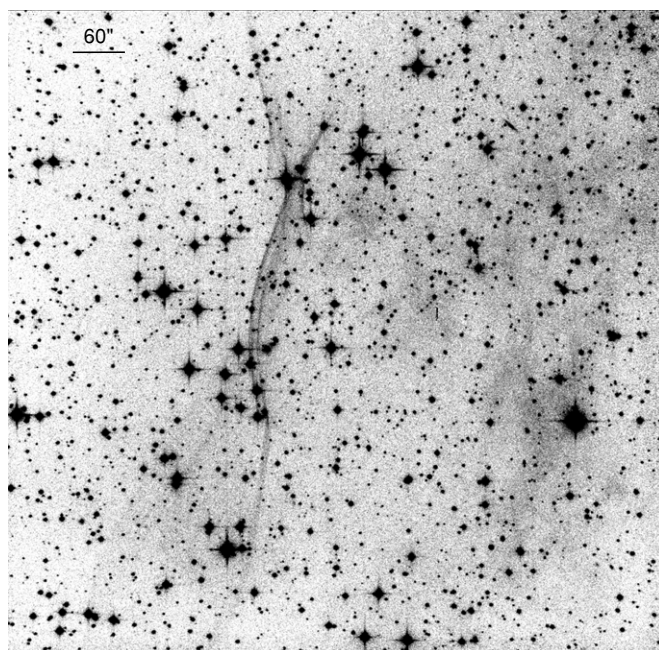
#### 3.1. A New Galactic Supernova Remnant

Both the morphology and spectra of the optical filaments seen in regions 1 and 2 (Figures 3 and 4) are consistent with a Balmer-dominated shock interpretation. Consequently, we propose that these optical filaments indicate that the large G159 emission shell is a previously unrecognized Galactic SNR. Considering these filaments' locations along the edge of the large  $H\alpha$  shell, the observed blueshifted velocities of the  $H\alpha$  emission suggest

<sup>1</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation. The Space Telescope Science Data Analysis System (STSDAS) is distributed by the Space Telescope Science Institute.



**Figure 3.**  $H\alpha$  image of region 1 in G159.6+7.3. North is up; east is to the left. The slit location on the short southeastern filament where we obtained a low dispersion spectrum (see Figure 5) is marked. Approximate center of image is  $\alpha(\text{J2000}) = 05^{\text{h}}31^{\text{m}}58^{\text{s}}.0$ ,  $\delta(\text{J2000}) = +49^{\circ}50'32''$ .



**Figure 4.**  $H\alpha$  image of region 2 in G159.6+7.3. Approximate center of image is  $\alpha(\text{J2000}) = 05^{\text{h}}34^{\text{m}}12^{\text{s}}.9$ ,  $\delta(\text{J2000}) = +49^{\circ}54'57''$ . North is up; east is to the left.

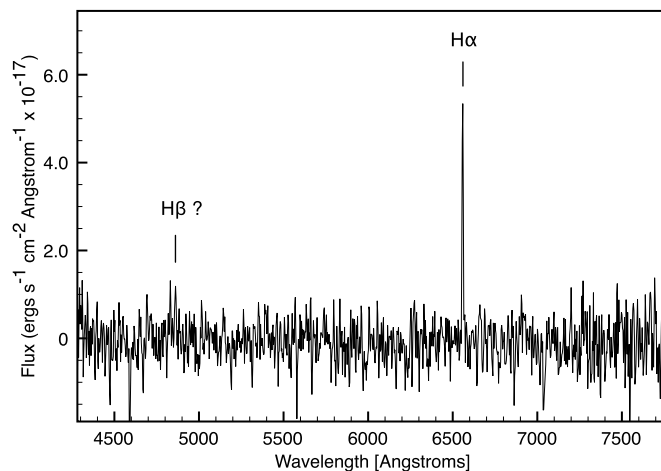
shock velocities in excess of  $\sim 200 \text{ km s}^{-1}$ . Although there is no reported non-thermal radio emission suggesting the presence of an SNR, the shell's location of more than  $7^{\circ}$  off the Galactic plane, and hence maybe in a region of relatively low interstellar density, may account for the lack of reported associated radio emission.

With shock velocities above  $200 \text{ km s}^{-1}$  implied by our optical spectra, some associated X-ray emission, albeit weak, is anticipated and we have possibly found faint associated X-ray emission to the G159 shell. Examination of online *ROSAT* All Sky Survey data (g180p00r5b120pm.fits) shows the possible presence of extremely faint diffuse emission coincident with the shell's central region. This is shown in Figure 6 where we present in the upper panel a wide, low angular resolution *ROSAT* 0.5–2.0 keV image of the G159 region with several well-known, neighboring Galactic SNRs marked. In the lower panels of Figure 6, we show smaller regions centered on G159 of the VTSS  $H\alpha$  image (left) and the *ROSAT* image (right).

While there are several other similar or even brighter extended emission patches within the large Galactic plane region shown in *ROSAT* 0.5–2.0 keV image (Figure 6, upper panel) which are not known to be associated with any Galactic SNRs, the rough coincidence of this faint emission patch (barely  $2\sigma$  above the X-ray background level immediately around it) with G159's central region is nonetheless interesting. Such an X-ray morphology would be consistent with that of a highly evolved SNR where the X-ray emission appears centrally filled (Shelton 1999; Williams et al. 2004). Although the X-ray flux from this emission patch is far too weak with which to produce a meaningful X-ray spectrum, its positional coincidence, size, and alignment with the G159 shell lends additional, albeit weak, support to G159's SNR identification.

### 3.2. G159's Distance, Size, and Evolutionary Phase

Although exceedingly faint, this new SNR exhibits several interesting properties. It would be only the second recently discovered optical SNR and would support Reich et al.'s (1979)

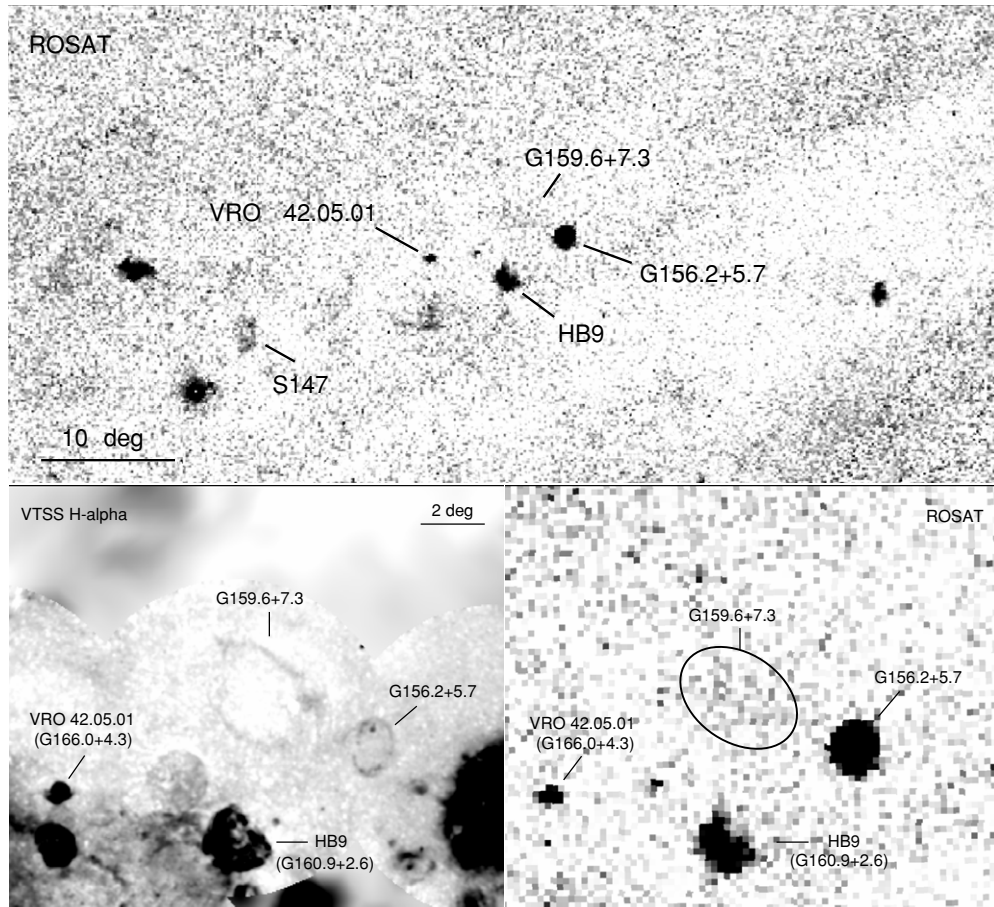


**Figure 5.** Optical spectrum of a relatively bright filament in G159.6+7.3 (see Figure 3) showing narrow  $H\alpha$  line emission.

suggestion that many other high-latitude SNRs could have escaped radio detection and identification. The remnant would also rank among the very largest Galactic SNRs known in angular size and have exceptionally weak radio emission.

In the current catalog of the 275 known Galactic SNRs, G159 has no analog in the sense that it is not the young remnant of a historic SN (like Tycho or SN 1006) yet shows only Balmer-dominated optical emission filaments, a property mainly seen in young SNRs. This raises questions about its age: is it really old as its large size would suggest with Balmer-dominated filaments much like those seen in parts of the Cygnus Loop, or could it be just a few 1000 yr old and thus be a larger, older version of the SN 1006 remnant? The SN 1006 remnant is expanding in a very low density interstellar medium (ISM) resulting in a high shock velocity suppressing the formation of common postshock optical cooling filaments.

Although G159's distance is unknown, we estimate an upper limit to its distance of  $\simeq 2 \text{ kpc}$  based on arguments regarding



**Figure 6.** Galactic plane around G159.6+7.3, with  $(l, b)$  increasing to the left and top, respectively. Top panel shows a wide field view of neighboring SNR X-ray sources as detected in the *ROSAT* All Sky Survey (RASS3). Note the presence of faint diffuse emission near the location of G159.6+7.3. The bottom panel shows enlargements of G159.6+7.3 region in the VTSS H $\alpha$  survey (left) and *ROSAT* X-ray image (right).

its likely maximum physical size. With angular dimensions of  $3^\circ \times 4^\circ$ , G159 is about the same angular size of the Cygnus Loop which lies at an estimated distance of  $\simeq 0.54$  kpc (Blair et al. 2005, 2009). If G159 is physically smaller and hence closer than the Cygnus Loop, then it would rank among the nearest SNRs known, perhaps just behind the Gum and Vela remnants at  $\sim 0.25$  kpc. If, on the other hand, G159 lies farther away than 1 kpc, its size would substantially exceed that of the Cygnus Loop and have a diameter in excess of 60 pc. From an observational perspective that there are few remnants with physical diameters greater than about 100 pc (Williams et al. 2004; Urošević et al. 2005; Cajko et al. 2009), and theoretical considerations for the radiative expansion phase at diameters around 150 pc or less (Cioffi et al. 1988; Slavin & Cox 1993; Shelton 1999), we suggest G159 lies at a distance less than 2.5 kpc. A range of 1–2.5 kpc would place it at a distance much like the 1.3–3.0 kpc estimated for its brighter neighboring SNR, G156.2+5.7 (Pfeffermann et al. 1991; Yamauchi et al. 1999). That remnant is somewhat unusual in that it exhibits, in addition to several ordinary radiative shock filaments, an extensive set of Balmer-dominated filaments (Gerardy & Fesen 2007) possibly for the same reason as in G159, namely, an expansion into large and relatively low density ISM regions.

Regardless of its actual distance, G159 is an interesting object. Being likely one of the larger Galactic SNRs known, the lack of reported radio emission from its shell is consistent with SNR evolutionary models which predict a rapid drop in radio emission in the radiative phase (Asvarov 2006) and observations

of extragalactic SNRs which suggest weak radio emission for SNRs expanding in low density media (Pannuti et al. 2002). However, the presence of optical Balmer-dominated filaments raises the question of how such a large and presumably old SNR has managed to avoid producing any significant optical radiative emission along virtually its entire large shell structure. Our failure to detect any filamentary emission except along the northeastern rim might mean that its shock velocity is generally less than  $70 \text{ km s}^{-1}$  and hence too weak to generate strong optical emission. However, the true cause of the paucity of optical filaments, radiative or nonradiative, is currently unknown. In any case, further study of this newly identified remnant may help resolve its overall properties which, in turn, may lead to a better estimate of the number of undetected old radio and X-ray faint SNRs located well off the Galactic plane.

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