DETECTION OF EXTENSIVE OPTICAL EMISSION FROM THE EXTREMELY RADIO FAINT GALACTIC SUPERNOVA REMNANT G182.4+4.3

ROBERT A. FESEN1, JACK M. M. NEUSTADT1,2, THOMAS G. HOW3, AND 2 CHRISTINE S. BLACK1

ABSTRACT

Wide-field Hα images of the radio faint Galactic supernova remnant G182.4+4.2 reveal a surprisingly extensive and complex emission structure, with an unusual series of broad and diffuse filaments along the remnant’s southwestern limb. Deep [O III] 5007 Å images reveal no appreciable remnant emission with the exception of a single filament coincident with the westernmost of the broad southwest filaments. The near total absence of [O III] emission suggests the majority of the remnant’s optical emission arises from relatively slow shocks (≤70 km s$^{-1}$), consistent with little or no associated X-ray emission. Low-dispersion optical spectra of several regions in the remnant’s main emission structure confirm a lack of appreciable [O III] emission and indicate [S II]/Hα line ratios of 0.73 – 1.03, consistent with a shock-heated origin. We find G182.4+4.2 to be a relatively large (d ~50 pc at 4 kpc) and much older (age ~40 kyr) supernova remnant than previously estimated, whose weak radio and X-ray emissions are related to its age, low shock velocity, and location in a low density region some 12 kpc out from the Galactic centre.

Subject headings: ISM: individual objects: G182.4+4.3, ISM: supernova remnant - shock waves - optical

1. INTRODUCTION

The majority of the nearly 300 currently identified Galactic supernova remnants (SNRs) were discovered at radio wavelengths due to their characteristic nonthermal radio emission associated with shocked gas. Of these, only some 30% exhibit any coincident optical emission.

Among the faintest radio Galactic SNRs known is G182.4+4.3. It was discovered by Kothes et al. (1998) using the Effelsberg 100 m radio telescope at frequencies of 1400, 2675, 4850, and 10450 MHz who found it to have a spectral index $\alpha = -0.42 \pm 0.10$ and a polarization percentage exceeding 60% for the brightest southwestern parts of its emission shell.

Based on the remnant’s bright southwestern limb at 1400 and 2675 MHz and a partially complete spherical shell weakly seen at 4850 MHz, Kothes et al. (1998) estimated a diameter of 50′. They also estimated a distance of at least 3 kpc, an age of 3800 yr, and a shock velocity of 2300 km s$^{-1}$ based upon an estimated relatively low ambient interstellar density, $n_0$, of less than 0.02 cm$^{-3}$ and a Sedov expansion model with a ratio of 5 to 10 for swept-up mass to ejected mass.

Follow-up observations made by Reich (2002) at 2.7 and 4.9 GHz and by Sun et al. (2011) at 6 cm determined $\alpha = -0.41 \pm 0.14$. CO observations made by Jeong et al. (2012) showed the boundary of a molecular cloud off to the remnant’s northeast limb that matched its radio boundary although no evidence for interaction was found.

Optical emission associated with the G182.4+4.3 was first reported by Sezer et al. (2012). Four 13.5′ × 13.5′ regions were imaged using on and off Hα and [S II] 6716,6731 narrow passband filters. These images, which covered portions of the remnant’s centre, southern, northern, and northwestern regions revealed both filamentary and diffuse emission which they found was correlated with the remnant’s radio structure.

The optical filaments exhibited [S II]/Hα ratios of 0.9 to 1.1 ±0.1 based on flux-calibrated images, well above the standard SNR [S II]/Hα ratio criteria of 0.4 (Mathewson & Clarke 1972, D’Odorico et al. 1980, Blair et al. 1981, Dopita et al. 1984), confirming the shocked nature of the detected optical emission. Sezer et al. (2012) also reported finding associated X-ray emission based on XMM-Newton data and estimated a relatively young age of just 4400 yr assuming a distance of 3 kpc.

No associated optical emission is visible on the emission-line survey of the Galactic plane of Parker et al. (1979) and the remnant’s Galactic region was not surveyed by the much deeper Virginia Tech Spectral Line Survey (VTSS) of the Galactic Plane (Dennison et al. 1998, Finkbeiner 2003). However, while a few of the remnant’s brighter filaments are visible in the Isaac Newton Telescope (INT) Photometric Hα Survey (IPHAS) of the Northern Galactic Plane (Drew et al. 2005, González-Solares et al. 2008), much of G182.4+4.3’s overall optical structure is surprisingly visible on the digitized broadband red image of the second Palomar Sky Survey (DSS2) (see Fig. 1).

Here we report a deep mapping of G182.4+4.3’s optical emission structure. Wide-field Hα images reveal an extensive optical structure from this extremely radio faint SNR, including considerable interior emission and a remarkable set of broad and diffuse optical shock filaments along its southwestern limb, plus a near total absence of [O III] line emission.

Our optical imaging data and follow-up low-dispersion spectra are described in §2, with results presented in §3. Combining these new data with prior optical and radio observations, we discuss in §4 the remnant’s general
properties including its distance, size, and shock velocity. Our conclusions are summarized in §5.

2. OBSERVATIONS

Wide-field images centred on the remnant G182.4+4.3 were obtained in February 2016 with a f/4 90 mm refractor at the Curdridge Observatory in Southampton, UK. The images were taken using an Astronom 30 Å FWHM Hα filter and an Atik 490 camera employing an Sony ICX814 CCD which was binned 2 × 2 yielding 1690 × 1352 pixels. This system provided a FOV of 64′ × 86′ with an image scale of 3.72′′ pixel−1.

By combining 25 dithered 1500 s exposures for a total exposure time of 10.4 hr, faint but extensive Hα emission was detected within the boundaries of the remnant’s radio emission. Similarly long 30 Å FWHM [O III] filter exposures showed little coincident emission with the exception of a single filament along its southwestern limb.

Based on these images, low-dispersion spectra of four filaments in the remnant’s northern, northern, southern and southern regions were subsequently obtained with the 2.4 m Hiltner telescope at MDM Observatory in January and February 2017 using the OSMOS Spectrograph (Martini et al. 2011). Using a blue VPH grism (R = 1600) and a 1.2 arcsec N-S slit, exposures of 2 × 1200 s and 2 × 2000 s were taken of four filament regions covering 3900–6900 Å with a spectral resolution of 1.2 Å pixel−1. Spectra were extracted from regions between 4 and 9 arcseconds along each of the slits.

Follow-up, higher resolution direct images were subsequently obtained on 22 February 2017 using the 1.3 m McGraw-Hill telescope at the MDM Observatory at Kitt Peak outside of Tucson, Arizona. A series of narrow passband Hα and red continuum 6450 Å images (FWHM = 90 Å) with exposure times of 900 s were taken covering most of the remnant’s northern and southern regions using a 2k × 2k SITe CCD providing a FOV of 17′ × 17′, with on-chip binning yielding an image scale of 1.06″ pixel−1.

Standard pipeline data reduction of MDM images and spectra using IRAF was performed. Spectra were similarly reduced using IRAF and the software L.A. Cosmic (van Dokkum 2001) to remove cosmic rays. Spectra were calibrated using an Ar lamp and spectroscopic standard stars (Oke 1974; Massey & Gronwall 1990).

3. RESULTS

3.1. Images

G182.4+4.3’s full Hα emission structure can been seen in the wide-field, low resolution images shown in Figure 1. Despite its extremely faint radio emission, the remnant exhibits an extensive optical emission structure, brightest in the south, southeast and northwest, with considerable and unusually bright interior emission. A circle 43′ in diameter centred at α(J2000) = 06:08:22.5, δ(J2000) = +28:58:45 (l = 182.46°, b = −4.31°) can encompass all of the remnant’s optical emission except for a small extension off the remnant’s northwestern limb.

In contrast to its extensive Hα emission, our deep [O III] 5007 Å image shows G182.4+4.3 to emit almost no [O III] line emission. Comparison of the remnant’s Hα and [O III] images, along with a 1.4 GHz NRAO VLA Sky Survey (NVSS; Condon et al. 1998) radio emission map is presented in Figure 2.

As can be seen in this figure, while the remnant shows considerable Hα emission, our [O III] image detected only a single [O III] emission filament. Although having nearly the same curvature as this westernmost Hα filament, the [O III] filament is not precisely coincident with it, but is instead offset farther to the west some 20′′ − 30′′ from the Hα filament. It also appears to extends a bit farther northward than that of the Hα filament.

Sezer et al. (2012) claimed the presence of XMM-Newton detected X-ray emission from an extended region some 16 arcminutes in diameter located along the remnant’s southwestern remnant centred on RA=06:07:10, Dec=+28:52:05 near and behind (East) of the location of the remnant’s sole [O III] bright filament. However, examination of ROSAT All-SKY Survey (RASS3; 0.5–2.0 keV) data could not confirm the presence of any appreciable X-ray associated emission with the remnant.

The lower panel of Figure 2 reveals a close correlation of the remnant’s brightest radio emission filament with its outermost southwestern Hα filament, along with a faint Hα filament in its eastern limb perhaps best seen in the DSS2 image shown in Figure 1, and the relatively bright complex of overlapping Hα filaments also in the East. We note that [O III] filament also roughly matches the position and extent the remnant’s bright southwestern 1.4 GHz radio emission filament.

Higher resolution views of the remnant’s southern and northern limbs are presented in the image mosaics of Figures 3 and 4. Hα and continuum subtracted Hα images are shown for both regions. Although Sezer et al. (2012) also imaged part of the remnant’s northern and southern limbs, more emission can be seen in these figures, especially in regard to interior emission. From their image data, Sezer et al. (2012) found diffuse interior emission especially in the north and central regions. However, our continuum subtracted images instead reveal a complex structure of short, faint and curved interior filaments that could be mistaken as diffuse emission.

While much of G182.4+4.3’s Hα emission structure is not exceptional compared to that seen in many other Galactic SNRs, the presence of so much optical emission for such a radio faint SNR is wholly unexpected. Moreover, the morphology of its broad and diffuse Hα filaments located further south and west of the remnant’s nominal emission structure is highly unusual. Whereas a continuous line of relatively bright filaments stretch from the remnant’s southeastern corner to its western limb that would seem to mark its southern boundary, several long and parallel filaments are seen considerably farther west.

These outer southwestern filaments give a sense of concentric shock fronts outside of the remnant’s otherwise seemingly well defined southwest boundary. They are also unusually broad and partially diffuse in appearance, exhibiting a brightness gradient with increasing distance behind their leading (western) edges. As noted above,
Fig. 1.— **Upper Panel:** A smoothed reproduction of the digitized red Palomar Sky Survey image (DSS2) revealing emission associated with the SNR G182.4+4.3. (A faint satellite trail running across the remnant has been digitally removed.) **Lower Panel:** A deep Hα image of the SNR G182.4+4.3 showing a more extensive optical emission structure along with an unusual series of broad filaments along its southwestern limb which is only hinted at in the DSS2 image. Note that the DSS2 image shows a more complete line of emission along the remnant’s northern boundary than seen in the Hα image.
the western edge of the more western filament is close to but not exactly coincident with the remnant’s sole [O III] filament.

The remnant’s northern Hα emission (Fig. 4) is generally fainter than in the south (Fig. 3), with the exception of a complex of brighter filaments along its northwestern limb. These filaments were partially imaged by Sezer et al. (2012). As can be seen in the continuum subtracted image and in the red DDS2 image (Fig. 1), the remnant’s Hα emission is nearly continuous along the northern limb.

3.2. Optical Spectra

Due to the relative faintness of the remnant’s optical emissions, low-dispersion spectra were only obtained at four regions on the remnant’s brighter northwestern and southern filaments. Exact slit positions are shown in the upper panels of Figure 5, with the resulting reduced spectra shown in the figure’s lower panels. Spectra of these regions showed [S II]/Hα ratios between 0.75 and 1.03 (±0.1), consistent with the earlier findings of Sezer et al. (2012) and well above the standard SNR identification criteria of ≥0.4 (D’Odorico et al. 1980; Blair et al. 1981; Dopita et al. 1984).

In the four filament spectra, the ratio of the density sensitive [S II] 6716, 6731 Å emission lines are all near
the low density limit of 1.43 (within measurement error), indicating postshock electron densities \( \leq 100 \text{ cm}^{-3} \) (Osterbrock & Ferland 2006). Also, consistent with the results of the direct imaging, none of the four spectra showed any appreciable \([\text{O III}] 4959, 5007 \text{ Å}\) emission.

Because \([\text{O I}] 6300, 6364 \text{ Å}\) emission is often seen in SNR spectra (Fesen et al. 1985), the lack of \([\text{O I}]\) in the spectra taken at slit positions South 2 and West deserves special comment. Although imperfect subtraction of the bright night sky \([\text{O I}]\) emission relative to the faintness of the remnant’s filaments could in principle account for the apparent lack of \([\text{O I}]\) emission at these two slit locations, no such issue was present for slit positions South 1 and Northwest (NW) where \([\text{O I}]\) emission was clearly detected. In addition, a careful examination did not indicate background \([\text{O I}]\) sky emission subtraction problems at either slit position. Rather, background subtraction of extended \([\text{O I}]\) emission from surrounding remnant filaments may have led to the seeming absence of \([\text{O I}]\) in these faint filaments. We note that the presence of some filaments elsewhere in the remnant exhibiting relatively strong \([\text{O I}]\) emission might account for some differences in the remnant’s morphology seen in the broadband red DSS2 image versus our \(\text{H} \alpha\) image (see Fig. 1). Hence, we conclude it likely that many, if not most, of the remnant’s filaments exhibit some \([\text{O I}]\) emission as expected from shocked interstellar gas.

We detected \(\text{H} \beta\) emission in three of the filaments studied and thus can estimate the reddening in these directions. The observed \(\text{H} \alpha/\text{H} \beta\) ratios for the filamentary emissions at slit positions South 1, South 2, and NW are 4.54, 3.40, and 4.35, respectively. Assuming a temperature of 10,000 K and an intrinsic \(\text{H} \alpha/\text{H} \beta\) ratio of 2.87, these values suggest a range of \(E(B-V)\) values between 0.17 and 0.43 (see Table 1).

4. DISCUSSION

G182.4+4.3’s extensive and relatively bright optical structure is surprising given its very faint radio emission which places it in the bottom 1% of the almost 300 known Galactic SNRs (Green 2015). No other Galactic SNR with such a low surface brightness near G182.4+4.3’s value of \(\Sigma 1 \text{ GHz} = 7.5 \times 10^{-23} \text{ Watt m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}\) (Kothes et al. 1998) shows nearly as extensive optical
emission, if they show any detectable optical emission at all (Green 2014).

The remnant is also unusual in showing long, smoothly curved and parallel Hα filaments along its southwestern and western limbs which are quite unlike that seen in any other Galactic SNR. We speculate that these curiously parallel filaments may indicate a large-scale blowout of the remnant’s shock front in this direction. Moreover, the presence of separate filaments may also indicate small ISM density variations along our line of sight.

The remnant’s overall near total lack of appreciable [O III] emission is also relatively rare. Optical spectra of Galactic and extragalactic SNRs reveals only a handful of remnants that globally exhibit no [O III] emission. In those cases, the remnants are both physically large and estimated to be relatively old (Fesen et al. 1985, Long et al. 2018).

It is interesting to note that the remnant’s sole [O III]
Fig. 5.— Upper panels: Locations of the four slit positions. Lower panels: Optical spectra for the four slit positions.
emission filament is not exactly coincident with the outermost southwest Hα filament. Instead, it is displaced by some 20 to 30 arc seconds farther west yet in alignment in size and extent with the remnant’s brightest radio emission. This could be a sign of significant post-shock cooling, signaling the remnant may be evolving out of the adiabatic and into the radiative phase.

The presence of strong [S II] and [N II] emissions but weak or absent [O III] emission is a signature of relatively low shock velocities (<70 km s$^{-1}$) (Raymond 1979; Shull & McKee 1979; Hartigan et al. 1987). However, such a conclusion is contrary to earlier estimates for G182.4+4.3’s properties where it has been suggested to be a relatively young SNR with a shock velocity around 2000 km s$^{-1}$ (Kothes et al. 1998; Sezer et al. 2012).

Knowledge of G182.4+4.3 true physical size would greatly aid in determining its evolutionary phase but this is unknown due to its uncertain distance. Kothes et al. (1998) estimated a distance of at least 3 kpc, whereas Gusenov et al. (2003) cites a value of 4.83 kpc and Pavlovic et al. (2013, 2014) a value of 4.2 – 4.4 kpc based on various versions of a $\Sigma - D$ relation.

With an angular diameter of approximately 43' based on our optical images, G182.4+4.3 would have a linear diameter of around 38 pc if placed at its initial estimated minimum distance of 3 kpc (Kothes et al. 1998; Sezer et al. 2012). However, a distance in excess of 3 kpc seems likely.

One can use our derived $E(B - V)$ reddening values from our optical spectra to help determine its distance through reddening values as a function of distance from the three-dimensional maps presented in Green et al. (2015) which utilized Pan-STARRS (Schlafly et al. 2014) and 2MASS (Skrutskie et al. 2006) photometry. Spectra of remnant’s southern filaments showed $E(B - V)$ values between 0.17 and 0.43 (see Table 1). This range is consistent with distances anywhere from 0.5 to 4.0 kpc. However, given the weakness of and low S/N for Hβ in our three spectra, the fact that two filaments (NW and South 1) indicate similar $E(B - V)$ values of around 0.40 suggests a distance of 4 kpc or more.

If one takes the remnant to be in the adiabatic Sedov-Taylor phase of its evolution, then its radius, R, in pc is equal to: 12.5 $E_{51}^{-1/5}$ $n_{o}^{-1/5}$ $t_{1000yr}^{2/5}$ and its shock velocity, $V_{shock}$, is equal to: 1950 km s$^{-1}$ $E_{51}^{1/5}$ $n_{o}^{-1/5}$ $t_{1000yr}^{-3/5}$, where $E_{51}$ is the SN energy release in units of 10$^{51}$ erg and $n_{o}$ is electron density in cm$^{-3}$ (Blondin et al. 1998). Adopting a distance of 3 kpc and hence a linear radius of 19 pc, $E_{51} = 1$, and $n_{o} = 0.02$ cm$^{-3}$ as estimated from radio observations (Kothes et al. 1998; Sezer et al. 2012), one finds an age $\sim$4000 yr and a shock velocity $\sim$650 km s$^{-1}$. Similar age and shock velocities for G182.4+4.3 were estimated by Kothes et al. (1998) and Sezer et al. (2012).

However, such a young age and relatively high shock velocity appear inconsistent with the remnant’s overall emission properties. Namely, its near total absence of optical [O III] line emission which points to a relatively slow, not fast, shock velocity and its weak radio and X-ray fluxes.

Moreover, if the remnant had a shock velocity of $\sim$2000 km s$^{-1}$, one would also expect to find widespread nonradiative Balmer dominated filament emissions like those seen in the remnants of Tycho’s SNR (SN 1572) and SN 1006 (Kirshner et al. 1987; Ghavamian et al. 2002) especially along its limbs. Instead we find, as did Sezer et al. (2012), ordinary shocked SNR optical emission filaments with strong emission from low ionization states such as [N II] and [S II].

On the other hand, if the remnant were at a distance around 4 kpc, as suggested based on $\Sigma - D$ estimates, the remnant would be roughly some 50 pc in diameter and hence a larger, older and more evolved SNR. This would also put it more in line with its lack of appreciable [O III] emission due to expected lower filament shock velocities.

If one adopts an ISM density of 0.5 cm$^{-3}$ and assumes the remnant is in the Sedov phase, then a diameter of 50 pc and a SN energy of 1 x 10$^{51}$ erg leads to an estimated age of 40,000 yr and a blast wave velocity $\sim$250 km s$^{-1}$. This would mean the remnant is older and more slowly expanding than previously estimated.

The remnant’s overall optical line emissions also suggest a distance in excess of 3 kpc and hence a fairly old and large remnant. Compared to observed optical line ratios seen in other Galactic SNRs (González 1983; Fesen et al. 1985), our measured G182.4+4.3 values for [N II]/Hα ratio of between 0.5 and 0.6 and [S II] 6716/6731 implying a low interstellar density (see Table 1) are consistent with a relatively large remnant ($d \sim$50 pc) and a galactocentric distance of between 11 and 14 kpc. The combination of a [N II]/Hα ratio around 0.55 and [S II] 6716/6731 ratios at the low density limit of 1.43 place G182.4+4.3 at the extreme range of such values for Galactic SNRs (see Fig. 6 in Fesen et al. 1985).

Such an old, large remnant with a comparatively low shock velocity throughout much of its structure is also more in line with our observations regarding [O III] emission. Given its lack of [O III] emission, a shock velocity of 50 – 60 km s$^{-1}$ could be responsible for the observed optical spectrum seen for the majority of its optical filaments.

The exception is the remnant’s [O III] bright filament along its southwestern limb, coincident with the remnant’s brightest radio emission. Without having a spectrum of it we cannot estimate its shock velocity. However, models indicate that shocks above 80 km s$^{-1}$ are required to generate appreciable [O III] line emission (Raymond 1979; Shull & McKee 1979; Hartigan et al. 1987). The cause for a higher shock velocity along the remnant’s southwestern limb might be a lower density region that the remnant is expanding into.

In old SNRs, optical filaments typically have a preshock density several times the average ambient density, e.g., $1 - 10$ cm$^{-3}$. Equating ram pressures where $p_{1} v_{1}^2 = p_{2} v_{2}^2$, a 250 km s$^{-1}$ shock moving through a 0.5 cm$^{-3}$ medium will drive a 65 km s$^{-1}$ shock through a cloud of density $\sim 7$ cm$^{-3}$.

We note that with a size and age around 50 pc and 40 kyr, respectively, G182.4+4.3 might have evolved out of its adiabatic phase and into the radiative or snowplow phase. This could help explain its relatively extensive optical emission despite its weak radio flux (Cox 1972). In any case, we suggest that G182.4+4.3 is not a young SNR but instead a relatively large, old and well evolved...
and 12 kpc out from the Galactic centre.

SNR with weak emissions due to its old age, relatively low shock velocity, and location in a relatively low density SNR with weak emissions due to its old age, relatively faint radio supernova remnant G182.4+4.2. Deep \( \text{H} \alpha \) line ratios indicative of shock-heated gas and confirm the absence of \([\text{O III}]\) emission, suggesting that a relatively low velocity shock (\( \leq 70 \text{ km s}^{-1} \)) is wide spread throughout most of the remnant. From reddening estimates derived from our spectra along with published \( \Sigma - D \) distance estimates, we find G182.4+4.2 likely likely lies at a distance around 4 kpc and thus is a relatively large (\( d \approx 50 \text{ pc} \)) and old SNR with an age around 40 kyr whose faint radio emission and unusual optical spectra are related to its age, low density interstellar environment, and relatively low shock velocity.

5. CONCLUSIONS

We report the presence of a surprisingly extensive optical emission structure associated with the extremely faint radio supernova remnant G182.4+4.2. Deep \( \text{H} \alpha \) images reveal a complex and nearly complete emission shell \( \approx 43' \) in diameter, a set of unusually broad and diffuse filaments outside the remnant’s southwestern limb, and an almost complete lack of measurable \([\text{O III}]\) emission with the exception of a single long filament coincident with the remnant’s westernmost \( \text{H} \alpha \) filaments and brightest radio emission limb. Low-dispersion optical spectra of four regions show \([\text{S II}] / \text{H} \alpha \) line ratios indicative of shock-heated gas and confirm the absence of \([\text{O III}]\) emission, suggesting that a relatively low velocity shock (\( \leq 70 \text{ km s}^{-1} \)) is wide spread throughout most of the remnant. From reddening estimates derived from our spectra along with published \( \Sigma - D \) distance estimates, we find G182.4+4.2 likely likely lies at a distance around 4 kpc and thus is a relatively large (\( d \approx 50 \text{ pc} \)) and old SNR with an age around 40 kyr whose faint radio emission and unusual optical spectra are related to its age, low density interstellar environment, and relatively low shock velocity.

We thank the referee for many helpful suggestions, Dave Green for comments regarding G182.4+4.2’s faint radio emission, Jessica Khusmeyer for help in obtaining the optical spectra and the MDM Observatory staff for their excellent instrument assistance. This research was made possible by funds from the NASA Space Grant, the Jonathan Weed Fund, the Denis G. Sullivan Fund, and Dartmouth’s School of Graduate and Advance Studies.

REFERENCES

Blair, W. P., Kirshner, R. P., & Chevalier, R. A. 1981, ApJ, 247, 97
Blondin, J. M., Wright, E. B., Borkowski, K. J., & Reynolds, S. P. 1998, ApJ, 500, 342
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693
Cox, D. P. 1972, ApJ, 178, 150
Dennison, B., Simonetti, J. H., & Topasna, G. A. 1998, Publications of the Astronomical Society of Australia, 15, 147
Dopita, M. A., Binette, L., Dodoerico, S., & Benvenuti, P. 1984, ApJ, 276, 653
D’Odorico, S., Dopita, M. A., & Benvenuti, P. 1980, A&AS, 40, 67
Drew, J. E., Greimel, R., Irwin, M. J., et al. 2005, MNRAS, 362, 753
Fesen, R. A., Blair, W. P., & Kirshner, R. P. 1985, ApJ, 292, 29
Finkbeiner, D. P. 2003, ApJS, 146, 407
Ghavamian, P., Winkler, P. F., Raymond, J. C., & Long, K. S. 2002, ApJ, 572, 888
Gonzalez, J. 1983, Rev. Mexicana Astron. Astrofis., 5, 289
Gonzalez-Solares, E. A., Walton, N. A., Greimel, R., et al. 2008, MNRAS, 388, 89
Green, D. A. 2014, Bulletin of the Astronomical Society of India, 42, 47
Green, D. A. 2015, MNRAS, 454, 1517
Green, G. M., Schaffly, E. F., Finkbeiner, D. P., et al. 2015, ApJ, 810, 25
Guseinov, O. H., Ankay, A., Sezer, A., & Tagieva, S. O. 2003, Astronomical and Astrophysical Transactions, 22, 273
Hartigan, P., Raymond, J., & Hartmann, L. 1987, ApJ, 316, 323
Jeong, I.-G., Byun, D.-Y., Koo, B.-C., et al. 2012, Ap&SS, 342, 389
Kirshner, R., Winkler, P. F., & Chevalier, R. A. 1987, ApJ, 315, L135
Kothes, R., Forst, E., & Reich, W. 1998, A&A, 331, 661
Long, K. S., Blair, W. P., Milisavljevic, D., Raymond, J. C., & Winkler, P. F. 2018, ApJ, 855, 140
Martini, P., Stoll, R., Derwent, M. A., et al. 2011, PASP, 123, 187
Massey, P., & Gronwall, C. 1990, ApJ, 358, 344
Mathewson, D. S., & Clarke, J. N. 1972, ApJ, 178, L105
Oke, J. B. 1974, ApJS, 27, 21
Osterbrock, D. E., & Ferland, G. J. 2006, Astrophysics of gaseous nebulae and active galactic nuclei, 2nd. ed. Sausalito, CA: University Science Books
Parker, R. A. R., Gull, T. R., & Kirshner, R. P. 1979, NASA SP-434
Pavlovic, M. Z., Urosevic, D., Vukotic, B., Arbutina, B., & Goker, S. P. 1998, ApJ, 500, 342
Pavlovic, M. Z., Dobardzic, A., Vukotic, B., & Urosevic, D. 2014, in Neutron Stars, Pulsars, and Supernova Remnants, MPE Report 278 eds. W. Becker, H. Lesch, & J. Trümpler, pg 1
Schlafly, E. F., Green, G., Finkbeiner, D. P., et al. 2014, ApJ, 789, 15
Sezer, A., Gok, F., & Aktekin, E. 2012, MNRAS, 427, 1168
Shull, J. M., & McKee, C. F. 1979, ApJ, 237, 131
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Sun, X. H., Reich, P., Reich, W., et al. 2011, A&A, 536, A83
van Dokkum, P. G. 2001, PASP, 113, 1420