



## Research Article

# Investigating unusual H $\alpha$ features towards the Scutum Supershell

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### Abstract

We investigate the unusual H $\alpha$  features found towards the Scutum Supershell via recent arc-minute and arc-second resolution imaging. These multi-degree features resemble a long central spine ending in a bow-shock morphology. We performed a multi-wavelength study in [S II] optical, radio continuum, infrared continuum, HI, CO, X-ray, and gamma-ray emissions. Interestingly, we found the Galactic worm GW 16.9–3.8 HI feature appears within the Scutum Supershell, and likely influences the spine morphology. Furthermore, the rightmost edge of the bow-shock H $\alpha$  emission overlaps with [S II] line emission, 4.85 GHz radio, and both 60 and 100  $\mu$ m infrared continuum emissions, suggesting some potential for excitation by shock heating. We estimated the photo-ionisation from O-type and B-type stars in the region (including those from the OB associations Ser OB1B, Ser OB2, and Sct OB3) and found that this mechanism could supply the excitation to account for the observed H $\alpha$  luminosity of the spine and bow-shock of  $\sim 1\text{--}2 \times 10^{36}$  erg s<sup>-1</sup> (d/2.5 kpc)<sup>2</sup>. Recent MHD simulations by Drozdov et al. (2022) demonstrate the potential for supernova events to drive outflow and bow-shock types of features of the same energetic nature and physical scale as the H $\alpha$  emission we observe here. While this clearly requires many supernova events over time, we speculate that one contributing event could have come from the presumably energetic supernova (hypernova) birth of the magnetar tentatively identified in the X-ray binary LS 5039.

**Keywords:** H $\alpha$ ; OB association; early-type stars; HI shells; photo-ionisation; ISM: jets and outflows

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### 1. Introduction

Supershells – expanding cavities in neutral hydrogen – are highly energetic features in the interstellar medium (ISM), which extend to hundreds of parsecs away from the Galactic plane. The formation of a supershell can arise from stellar winds of O- or B-type stars (Heiles 1979), with additional energy coming from supernova or hypernova events from the core collapse of these massive stars (Perna & Raymond 2000). These processes can push the neutral ISM away from the Galactic plane (in particular the atomic gas traced by the 21 cm HI line). As a result, long ‘chimney’ HI features, possibly enhanced by Rayleigh-Taylor instabilities, can extend beyond the Galactic plane. Related linear ‘worm’ features in the HI gas may also form as the supershell breaks up (see e.g. de Avillez & Berry 2001; Dawson 2013). Ionised gas, traced by the optical H $\alpha$  line, has also been associated with supershells (Dennison, Topasna, & Simonetti 1997; Moldón et al. 2012). The Milky Way is host to several dozen known HI supershells with mechanical energies of  $> 10^{52}$  erg (see Table C1 for a list of Galactic supershells including their estimated energy and distance).

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The Scutum Supershell GSH 018–04+44 (Heiles 1979; Bonnarel et al. 2000) is one of the most energetic supershells. Callaway et al. (2000) provided the most detailed study of this supershell so far, estimating its distance at 3.3 kpc with a physical extension of approximately 290 pc based on its HI morphology. The supershell has an HI density of about 4/cm<sup>3</sup> and a total energy of  $1.1 \times 10^{52}$  erg. Several supernova remnants (SNRs) and HII regions were identified around or within the supershell.

Multiple OB associations are present in this region, which can host supernova events that feed energy into the supershell. The catalogue of OB associations by Humphreys (1978) lists Ser OB and Sct OB3 within a few degrees north of the Scutum Supershell. A later catalogue by Mel’Nik & Efremov (1995) suggests that Ser OB is actually three separate OB associations (Ser OB1A, Ser OB1B, and Ser OB2). Koo, Heiles, & Reach (1992) have suggested that these associations are potential energy sources of the Scutum Supershell.

Based on observations from the Wisconsin H $\alpha$  Mapper (WHAM) survey, Callaway et al. (2000) also revealed an ‘optical blowout’ phenomenon. They suggested that this was generated by a combination of SNRs, strong winds from O and B stars, and HII regions. They also noted the presence of hot ionised gas within the supershell, based on the presence of thermal X-ray emission that is spatially anti-correlates with the associated HI gas.

Several Galactic supershells feature optical H $\alpha$  emission and associated filaments. For instance, GSH 305+01–24 is an energetic

supershell with  $H\alpha$  emission detected towards the inner side of its HI shell (Kaltcheva, Golev, & Moran 2014). Other examples, featuring both  $H\alpha$  and HI emission, are the supershells GSH 006-15+7 (Moss *et al.* 2012), the Carina Flare (Fukui *et al.* 1999; Dawson *et al.* 2008), and the W4 HI region and its Superbubble (Dennison *et al.* 1997; Lagrois & Joncas 2009). In general, it is assumed that the  $H\alpha$  emission, tracing the warm ionised medium, is formed due to ionisation by the stellar photons and/or winds from O and B stars (e.g. Madsen, Reynolds, & Haffner 2006; Dawson 2013).

Since the study by Callaway *et al.* (2000), improved-quality (in terms of resolution and sensitivity) and new data in the radio (HI and continuum), infrared, optical ( $H\alpha$  and S[II] spectral lines), and X-ray bands have become available. Additionally, the population of energetic sources towards the Scutum Supershell (besides the O and B stars and SNRs discussed by Callaway *et al.* 2000) now includes a number of gamma-ray sources detected in the GeV to TeV energy bands, such as the pulsar wind nebulae (PWN) HESS J1825–137 and HESS J1826–130 (Abdalla *et al.* 2018; Collins *et al.* 2021, and references within), plus the High-Mass X-ray Binary LS 5039 (Aharonian *et al.* 2006) which has been suggested to be a magnetar (Yoneda *et al.* 2020).

Intriguingly, a part of the extended  $H\alpha$  emission in this region was attributed to a shock from SNR G18.7–2.2 based on the [S II]/ $H\alpha$  emission ratio (Stupar, Parker, & Filipovic 2008). This SNR was then postulated by Voisin *et al.* (2016) to have formed from the progenitor supernova event that also gave birth to the pulsar powering the prominent TeV-bright PWN HESS J1825–137.

Given the higher-quality and additional observations available, plus the discovery of several high-energy sources towards the Scutum Supershell (Abdalla *et al.* 2018), a new investigation of the  $H\alpha$  features towards the Scutum Supershell is warranted.

## 2. Data

We made use of publicly available data across the wavebands of interest:  $H\alpha$ , HI, infrared continuum,  $^{12}\text{CO}$ , radio continuum, X-rays, and gamma rays. Additionally, we have performed new  $H\alpha$  and S[II] emission line observations in an effort to further characterise the origin of the  $H\alpha$  emission.

The full-sky  $H\alpha$  map by Finkbeiner (2003) is a composite of three surveys: SHASSA (Gaustad *et al.* 2001), VTSS (Dennison, Simonetti, & Topasna 1998), and WHAM (Haffner *et al.* 2003). This composite map features an angular resolution of 6 arcmin. The WHAM observations by themselves provide  $H\alpha$  intensities for different velocities (with respect to the local standard of rest) with a resolution of 12 km/s, and covering a range from  $-150$  to 150 km/s (Reynolds *et al.* 1998). We also made use of the SuperCOSMOS  $H\alpha$  Survey (SHS) with the UK Schmidt Telescope (UKST) of the Anglo-Australian Observatory (AAO/UKST) with an angular resolution of 1–2 arcsec (Parker *et al.* 2005).

Our dedicated observations of  $H\alpha$  and [S II] utilised a Skywatcher Evolux 62ED refractor operating at  $f/5.6$  with a reducer/corrector lens, a ZWO ASI2600MM-Pro camera with  $3 \times 3$  pixel binning (resulting in a resolution of  $\sim 6$  arcsec per effective pixel), an Antlia 30Å  $H\alpha$  filter (transmission 90% at 656.3 nm; 38% at [N II] 654.8 nm, 25% at 658.3 nm), an Optolong 65Å [S II] filter (transmission 94% at [S II] 671.6 nm, and 96% at [S II] 673.1 nm) and a broadband R filter. Therefore, there will be some contamination from the [N II] lines in the  $H\alpha$  observations, and both [S II] lines are recorded for the [S II] observations. The [S II]

images were obtained over two nights, one in September 2022, and one in May 2023. For the 2022 observation, the exposure was 120 s, with 32 individual [S II] images being recorded. Short-exposure broadband R images were also recorded for continuum subtraction. During the 2023 observation, twelve 300 s [S II] exposures were taken, as well as a short-exposure R-band image. Thus, a total exposure time of the [S II] observations is 7440 s. Dark frames (to account for CCD noise) and flat-field frames (to correct uneven illumination) were obtained for each observing session. Intensity-scaled R-band images were subtracted from each night's stacked [S II] images. Image smoothing and bright/dark outlier reduction were applied in AstroImageJ (Collins *et al.* 2017) to reduce the noise in the image produced by imperfect continuum subtraction. Some inhomogeneities in the [S II] image remain, following flat-fielding and continuum subtraction. These are visible as large-angular-scale variations in brightness in the background. There are clear structures in the [S II] emission which are seen also in the  $H\alpha$  observations, so these imperfections do not negate the detection of the stronger [S II] features found in these observations.  $H\alpha$  imagery was obtained in July 2023, with 235 min of exposure time in a single night. A short R-band image was used for continuum subtraction. All intensities presented for our own  $H\alpha$  and [S II] imagery are arbitrary, as no standard sources were observed, and no flux calibration was applied.

For the HI gas, we made use of the Southern Galactic Plane Survey (SGPS) from the Parkes telescope (McClure-Griffiths *et al.* 2005), which extends to latitudes  $|b| \leq 10^\circ$  and covers most of the Scutum Supershell region. The spatial resolution (16 arcmin) and sensitivity (0.2 K per channel) of the SGPS data are better than those of the HI data used by Callaway *et al.* (2000) (21 arcmin and  $\sim 0.6$  K per channel), but have similar spectral resolution (0.8 km/s).

For the molecular hydrogen ( $\text{H}_2$ ) gas, we made use of the CfA-Chile combined carbon monoxide  $^{12}\text{CO}(J=1-0)$  Galactic plane survey (Dame, Hartmann, & Thaddeus 2001) which extends to  $|b| \leq 5^\circ$ . These observations have a spatial resolution of 8 arcmin,  $\sim 0.7$  km/s spectral resolution, and  $\sim 0.3$  K/channel sensitivity.

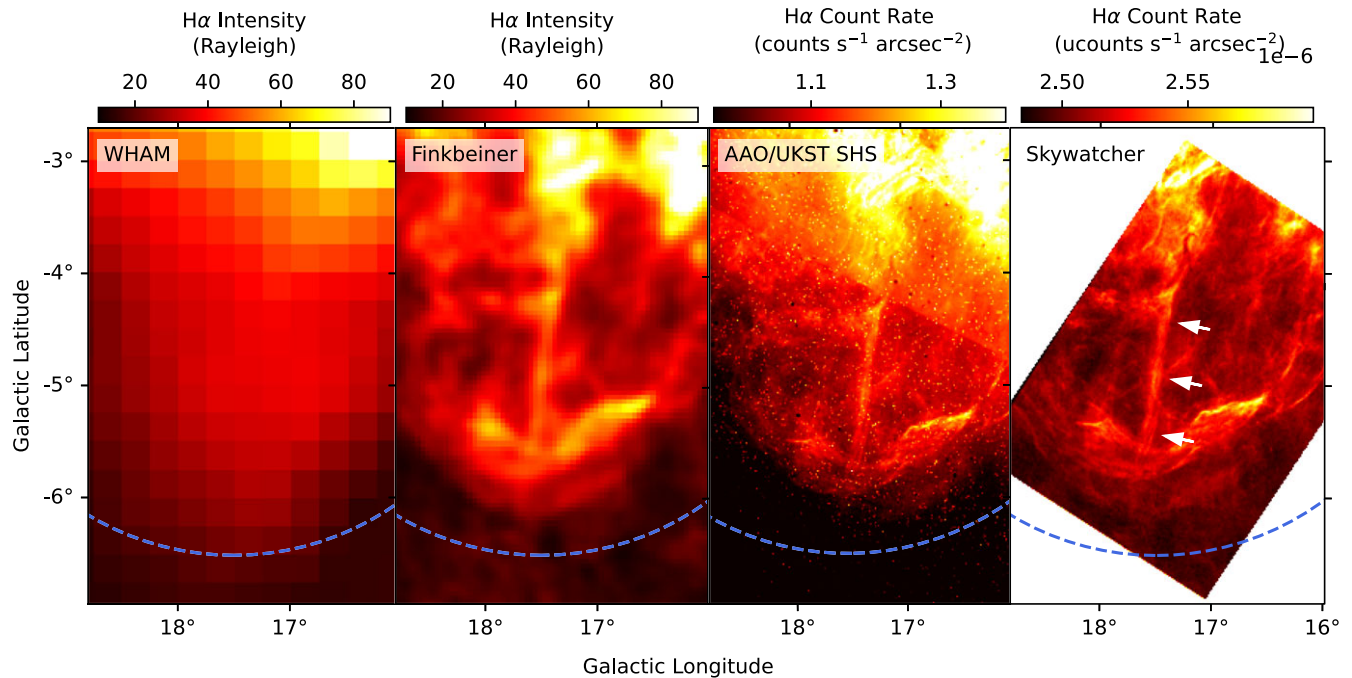
To study the radio continuum band, we made use of the Parkes-MIT-NRAO (PMN) survey, which was conducted at a frequency of 4.85 GHz (Griffith & Wright (1993); downloaded from ATNF<sup>a</sup>). The PMN survey has a resolution of 5 arcmin, which was oversampled to 1 arcmin per pixel.

For the infrared band, we use data from the Infrared Astronomical Satellite (IRIS) survey, observed at 12, 25, 60, and 100  $\mu\text{m}$  (Miville-Deschênes & Lagache 2005). The IRIS survey has a resolution of  $\sim 1$  arcmin.

For the X-ray investigations, we use the MAXI Solid-state Slit Camera (SSC) all-sky maps (Nakahira *et al.* (2020); available from HEASARC<sup>b</sup>). The MAXI SSC energy bands overlap those of the ROSAT Position Sensitive Proportional Counter (PSPC) All-Sky Survey data (RASS) (Voges 1993), which were used by Callaway *et al.* (2000) in their initial assessment of the X-ray emission towards the Scutum Supershell. The MAXI SSC observations were taken during the solar minimum period of 2009 to 2011 (Nakahira *et al.* 2020). In contrast, ROSAT PSPC was in operation from 1990 to 1991 (Snowden *et al.* 1995), including periods of high solar activity, which led to observations being affected by the Solar Wind Charge Exchange (SWCX) phenomenon (Snowden

<sup>a</sup><ftp://ftp.atnf.csiro.au/pub/data/pmn//maps/PMN/>.

<sup>b</sup><https://heasarc.gsfc.nasa.gov/docs/maxi/>.



**Figure 1.** Comparison of different observations of H $\alpha$  emission towards the Scutum Supershell (dashed blue circle). The observations refer to the WHAM survey (Haffner et al. 2003), the composite map derived by Finkbeiner (2003), the AAO/UKST SHS survey (Parker et al. 2005), and our own (uncalibrated counts labelled as ‘uncounts’) observations with the Skywatcher Evolux 62ED refractor with an H $\alpha$  filter. The ‘spine’ feature has a length of at least 2° and is highlighted by white arrows. The blowout morphology surrounding the spine is clearly revealed in the higher-resolution images. The bow-shock feature at the southern end of the spine is also evident in these images.

et al. 1997) (occurring when charged particles from the solar wind collide with neutral atoms in the Earth’s atmosphere, creating an interfering source of X-ray photons). According to Uprety et al. (2016), the contamination from the SWCX in ROSAT PSPC data decreases from about 26% to 6% across the 0.1 to 1.2 keV range, suggesting a preferential focus on the energies approaching 1 keV. The MAXI SSC observations feature an improved energy resolution of 0.1 keV at 1 keV (Tomida et al. 2011) compared to ROSAT PSPC’s 0.4 keV at 1 keV (Snowden et al. 1997). MAXI SSC provides maps in the 0.7–1.0 keV, 1.0–2.0 keV, and 2.0–4.0 keV energy bands, with a point spread function of 1.5° (Matsuoka et al. 2009).

Finally, to assess the TeV gamma-ray emission, we use the H.E.S.S. Galactic Plane Survey (HGPS; Abdalla et al. 2018). H.E.S.S. (High Energy Stereoscopic System) is an array of gamma-ray telescopes operating in an energy range from 30 GeV up to 30 TeV. The angular resolution of the HGPS is  $\sim 0.1^\circ$ , and the available flux maps provide the integral flux above 1 TeV. For the GeV gamma-ray emission, we made use of recent results (based on *Fermi*-LAT observations) from Araya, Mitchell, & Parsons (2019) and Collins et al. (2021), who reported several GeV sources adjacent to the TeV-bright PWN HESS J1825–137.

### 3. Results

Here, we present a comprehensive examination of the H $\alpha$  and other multi-wavelength data towards the Scutum Supershell.

#### 3.1 H $\alpha$ observations

Fig. 1 compares the H $\alpha$  emission of the different datasets. A linear feature is clearly resolved in the SHS and Skywatcher images and

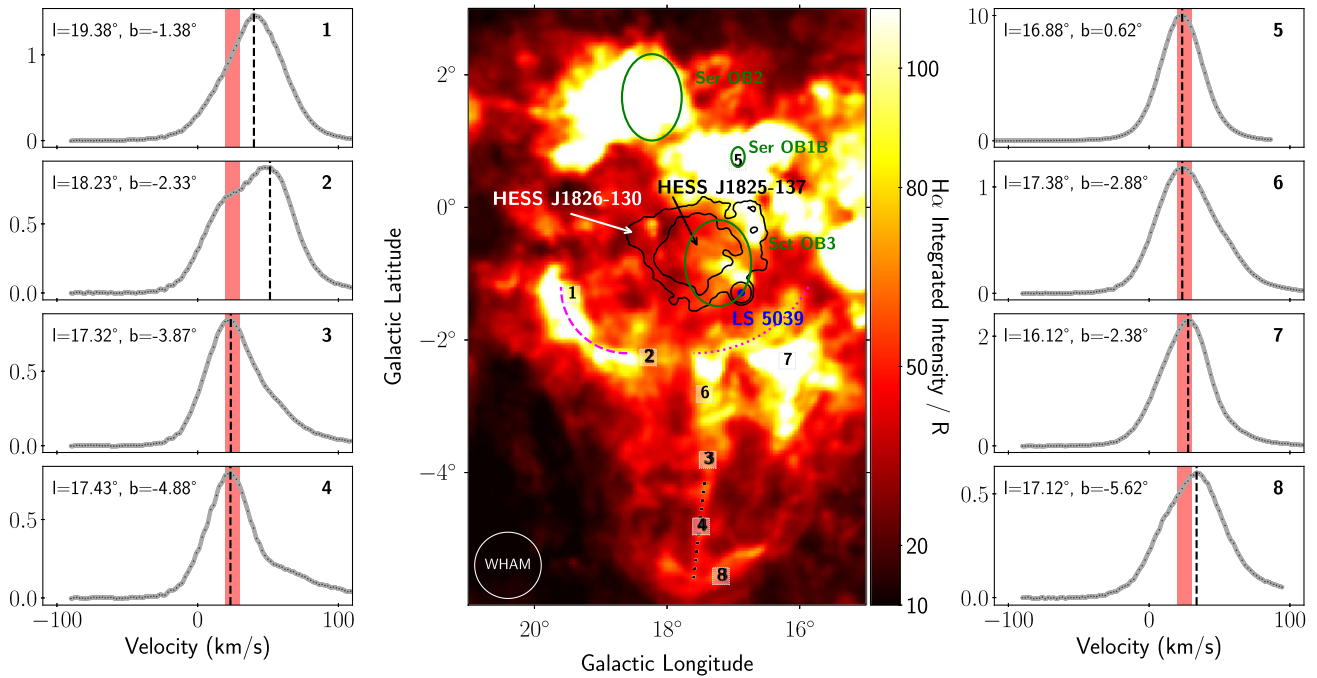
will be referred to as the ‘spine’. Additionally, the southern end of the blowout clearly shows increased H $\alpha$  emission. We label this feature the ‘bow-shock’ based on its apparent morphology. The linear spine feature appears to bisect the Scutum Supershell, and the bow-shock feature sits at the southern end of the spine and the southern boundary of the supershell.

As a follow-up to Figure 9 in Callaway et al. (2000), we show in Fig. 2 the H $\alpha$  image from Finkbeiner (2003) along with example spectral profiles taken from single WHAM pixels. The WHAM spatial FWHM of 1° is sufficient to spatially reveal the H $\alpha$  emission broadly along the outflow. Based on this, we investigate the spectral information in the WHAM data to indicate the distance to the features and to compare to molecular and atomic gas associated with the supershell.

First, we infer approximate kinematic distances based on the Doppler-shifted velocity  $v_{\max}$  at the intensity maximum of the spectral profile. To determine this velocity, we interpolate a function for each spectral profile using a B-spline<sup>c</sup>. First derivatives of the B-spline were then used to estimate the velocity ( $v_{\max}$ ) of the peak H $\alpha$  emission. Fig. 2 shows spectral H $\alpha$  profiles along with their  $v_{\max}$ . We show H $\alpha$  spectra along the spine (spectra #3, 4, 6), at the bow-shock to the south (spectrum #8), the OB association Ser OB1B, and the HII region G016.936+00.758 (spectrum #5). The HII region labelled S49 (see Fig. 9) is associated with the Messier 16 ‘Eagle Nebula’ and overlaps with spectrum #5. The velocity range 20–30 km/s (shaded red bands in spectra of Fig. 2) corresponds to a distance of about 2–3 kpc using the Galactic rotation curve model by Brand & Blitz (1993). The spectra #1 and #2

<sup>c</sup>sp1rep, sp1der, sproot from SciPy (Virtanen et al. 2020).





**Figure 2.** Wide view of optical  $H\alpha$  emission. *Middle:* Optical  $H\alpha$  image from Finkbeiner (2003) towards the Scutum Supershell. The TeV  $\gamma$ -ray significance contours obtained from HESS observations refer to the sources HESS J1825–137, HESS J1826–130, and LS 5039 (black contours of  $5\sigma$  and  $10\sigma$ ) (Abdalla et al. 2018). The OB associations Ser OB1B, Ser OB2, and Sct OB3 (Mel’Nik & Efremov 1995) are indicated as green ellipses. SNR G18.7–2.2 is indicated by a dashed magenta arc from Stupar et al. (2008) and dotted from Voisin et al. (2016). The dotted black line highlights the spine feature. *Left/right:* The eight panels show spectral profiles extracted from WHAM (Reynolds et al. 1998) for various pixels. The red-shaded band (20–30 km/s) indicates a kinematic distance of 2–3 kpc. The black dots and grey lines represent the  $H\alpha$  spectral intensities and B-spline interpolations. The vertical black dashed line indicates the velocity of the peak  $H\alpha$  emission,  $v_{\max}$ .

peak towards the 40–50 km/s range, consistent with a  $\sim 4$  kpc distance, however, the spectrum #2 features a second peak around 20–30 km/s. The  $H\alpha$  emission from these regions has been previously associated (Voisin et al. 2016; Stupar et al. 2008) with the possible progenitor of SNR G18.7–2.2 (see Fig. 2, magenta dashed arcs). This SNR is linked to the TeV gamma-ray source HESS J1825–137, and its distance is believed to be  $\sim 4$  kpc, based on the dispersion measure of the pulsar PSR J1826–1334 powering HESS J1825–137 and other interstellar gas studies by Voisin et al. (2016). The spectra from the other displayed regions (#3 to #8) peak within the 20–30 km/s range. Fig. 3 illustrates the peak velocities  $v_{\max}$  of each WHAM pixel for an extended region around the Scutum Superhshell. We can see that the  $H\alpha$  emission associated with the spine and bow-shock features is broadly found in the 20–30 km/s range.

Next, we investigate the different  $H\alpha$  spectral components in more detail. We employ GaussPy+ (Riener et al. 2019) to decompose each pixel’s spectrum into multiple Gaussian components (see Appendix A.2 for the results). The spectra are decomposed into up to five components; however, given WHAM’s poor spectral resolution of  $\Delta v = 12$  km/s (this also defines the minimum width of any Gaussian feature), and WHAM’s preprocessing including a spectral oversampling which leads to artefacts at large velocities  $\gtrsim 80$  km/s, we focused on the main (significant) components. We find that all spectra are decomposed into one or two main components. The spectra of the pixels encompassing the spine and bow-shock features have typically one main component peaking in the 20–30 km/s range, supporting our results from the analysis of the peak velocity and our estimate of associating the spine with a distance of 2–3 kpc.

From a visual inspection of the high-resolution  $H\alpha$  images, the spine is visible between Galactic latitudes of  $-5.5^\circ$  and  $-3.5^\circ$  for about  $2^\circ$  in length, which corresponds to a physical length of  $l \sim 70$  pc, assuming a 2.5 kpc distance. Unfortunately, the bright  $H\alpha$  emission further north associated with HII regions and other potential energetic objects (e.g. SNR shocks) complicates our determination if the spine extends further.

Some further insight into the origin of the  $H\alpha$  emission can come from the corresponding intrinsic luminosity. To extract the luminosity of the spine and of the bow-shock region, we used data from the  $H\alpha$  surveys WHAM, and Finkbeiner (2003). Background emission was estimated from several regions, as listed in Table A1, and was subtracted to estimate the luminosity above the local background. The luminosity  $L$  is estimated as  $L = 4\pi d^2 I$  for intensity  $I$  and distance  $d$ . We find  $H\alpha$  luminosities of

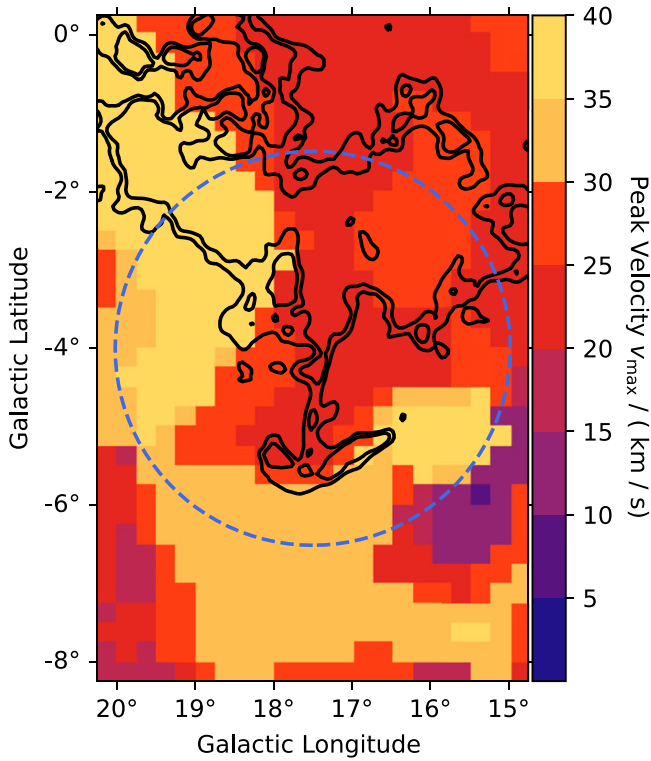
$$L_{H\alpha}(2.5 \text{ kpc}/d)^2 \sim 10^{36} \text{ erg/s};$$

see Table 1 for results of individual surveys and regions. For comparison, Table A2 provides  $H\alpha$  luminosities of other astrophysical objects that also exhibit  $H\alpha$  spine and bow-shock features, ranging from protostellar Herbig–Haro objects to X-ray binaries and active galaxies.

### 3.2 [S II] observations

In addition to the  $H\alpha$  emission, other lines such as [S II], [N II], and [O III] help to diagnose the role of shocks and photo-ionisation as the excitation mechanism for the gas. For example, Fesen, Blair, & Kirshner (1985) and Dopita (1977) demonstrate





**Figure 3.** Peak velocity distribution of WHAM H $\alpha$  emission spectra. The peak velocity  $v_{\max}$  is determined from the first derivative of a B-spline interpolation of each pixel's spectrum. The H $\alpha$  contours (black) indicate intensities of 40 and 50 Rayleigh from the Finkbeiner (2003) map, while the Scutum Supershell boundary is indicated by the dashed blue circle (Callaway et al. 2000).

that [S II] emission is an important indication of shocked gas from photo-ionised regions. This is due to the high electron temperature in the ionised sulphur S<sup>+</sup> zone of the shock, where non-equilibrium recombination occurs. The production of [S II] in a shock model requires a high shock velocity or gas pressure along with a high magnetic-field pressure (Raymond 1979).

Our work is the first to map the [S II] optical emission at arc-second resolution over this region, enabling a comparison with the H $\alpha$  emission. Fig. 4 clearly shows [S II] emission in the bow-shock region of the H $\alpha$  emission, peaking at the right side of the bow-shock. The emission line ratio [S II]/H $\alpha$  can be used to infer the physical conditions of the ionised gas (Raymond 1979), such as the potential for shock-excitation or photo-ionisation. However, since our [S II] observations are not flux-calibrated and our [S II] filter included both the [S II] 671.6 and 673.1 nm lines, we cannot determine this ratio.

### 3.3 Radio continuum observation

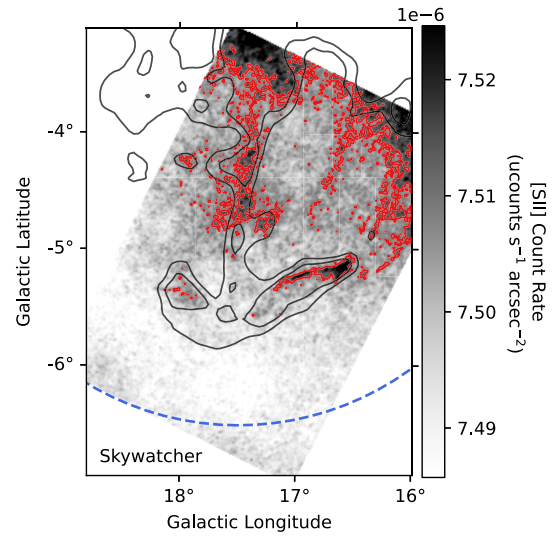
Fig. 5 shows the PMN 4.85 GHz survey (Griffith & Wright 1993) radio continuum emission. Interestingly, we find that the emission overlaps the brightest H $\alpha$  and [S II] emission at the right side of the bow-shock.

### 3.4 Infrared observations

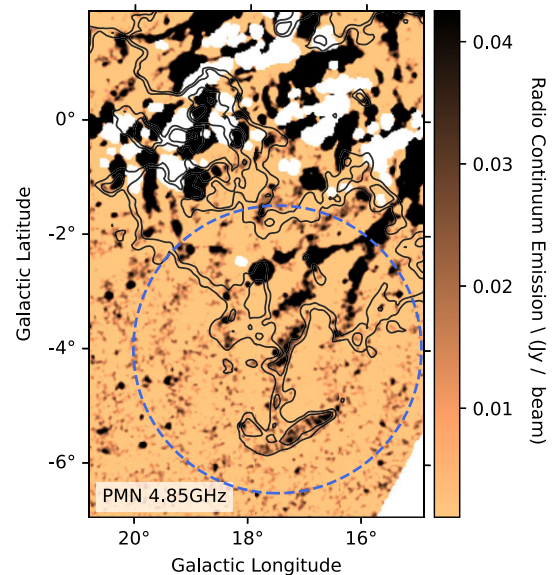
The IRIS (Miville-Deschênes & Lagache 2005) 12 and 25  $\mu$ m images did not show any significant emission towards the H $\alpha$  features. However, we observe emission (see Fig. 6) in the 60 and 100

**Table 1.** H $\alpha$  luminosities  $L_{H\alpha}$  for the spine and bow-shock features. Table A1 lists the signal and background regions and their corresponding extracted luminosities.

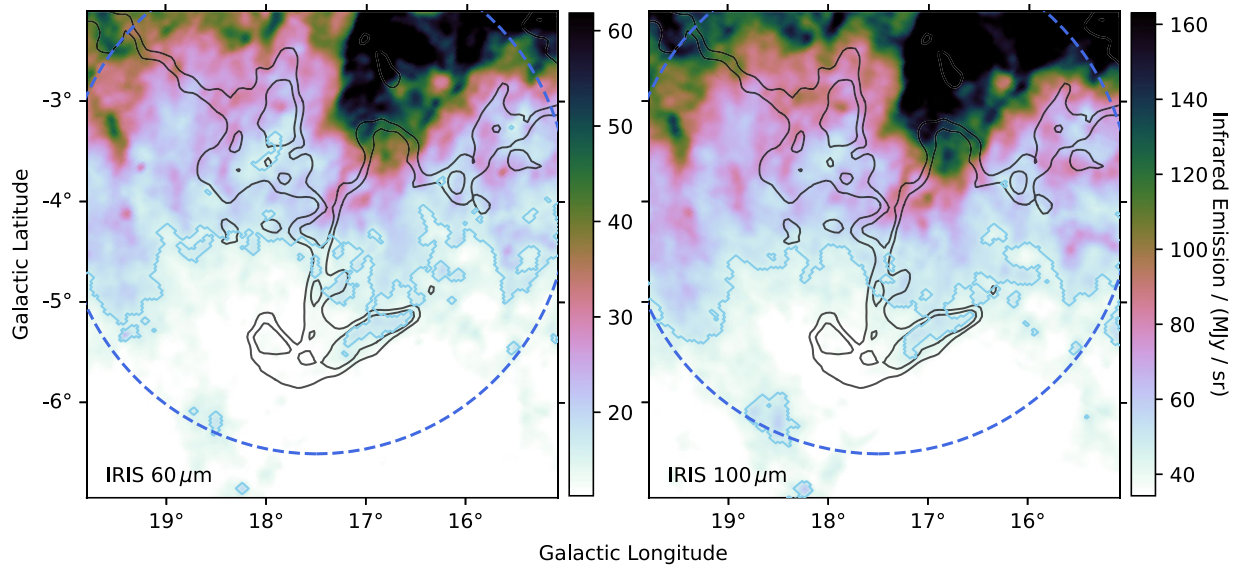
Region	$L_{H\alpha} (2.5 \text{ kpc} / d)^2$ ( $\text{erg s}^{-1}$ )
H $\alpha$ bow-shock (Finkbeiner)	$2.07 \times 10^{36}$
H $\alpha$ bow-shock (WHAM)	$1.31 \times 10^{36}$
H $\alpha$ spine (Finkbeiner)	$1.23 \times 10^{36}$
H $\alpha$ spine (WHAM)	$0.78 \times 10^{36}$



**Figure 4.** Skywatcher [S II] (uncalibrated) count rate towards the Scutum Supershell (dashed blue circle). The red contours indicate observations at  $5\sigma$  significance level. H $\alpha$  emission from the composite map at 40 and 50 R (Finkbeiner 2003) is illustrated as black contours.



**Figure 5.** PMN 4.85 GHz radio continuum emission towards the Scutum Supershell (dashed blue circle). H $\alpha$  emission (Finkbeiner 2003) at 40 and 50 Rayleigh is illustrated as black contours. Saturated pixels ( $>40$  Jy; Griffith & Wright 1993) are shown in white, as well as pixels outside the observed field.



**Figure 6.** IRIS infrared emission (Miville-Deschênes & Lagache 2005) in the  $60\ \mu\text{m}$  (left) and  $100\ \mu\text{m}$  (right) bands towards the  $\text{H}\alpha$  emission (black contours). Lightblue contours represent emission with a significance of  $5\sigma$ .

$\mu\text{m}$  observations towards the bow-shock region overlapping the brightest  $\text{H}\alpha$  and [S II] features and the 4.85 GHz radio continuum emission. The estimated fluxes for the region with significant infrared emission (right side of the bow-shock) are  $\sim 2.4 \times 10^{-5}$  MJy ( $60\ \mu\text{m}$ ) and  $\sim 6.1 \times 10^{-5}$  MJy ( $100\ \mu\text{m}$ ). For these flux density estimates, we subtracted a background estimate using the regions listed in Table A4.

### 3.5 Atomic and molecular hydrogen observations

As shown by Callaway et al. (2000), the HI emission reveals the atomic gas boundary associated with the Scutum Supershell. Fig. 7 shows HI column density distributions in the range between 10 and 50 km/s, each integrated over 10 km/s. For converting the HI brightness temperature to column density, we used the conversion factor from Dickey & Lockman (1990), which assumes optically thin HI emission.

In the 20–30 km/s range, we noticed that the Galactic worm GW 16.9–3.8, found by Koo et al. (1992) in HI emission, is adjacent to the  $\text{H}\alpha$  spine. With an estimated distance of 2.5 kpc, the worm has a length of 50–180 pc. Koo et al. (1992) and Callaway et al. (2000) suggested that this worm is at the foreground edge of the Scutum Supershell and may be driven by stellar winds or supernovae from the Ser OB1B association (Koo et al. 1992) (also indicated in Fig. 7).

The HI maps in the 10–30 km/s range also reveal strong emission towards the GeV B gamma-ray peak. The three GeV gamma-ray peaks, labelled GeV A, GeV B and GeV C, were discovered by Araya et al. (2019) in their analysis of *Fermi*-LAT GeV data. They noted that the three peaks are found several degrees south of the PWN HESS J1825–137 and Collins et al. (2021) considered their origin due to particles escaping the PWN.

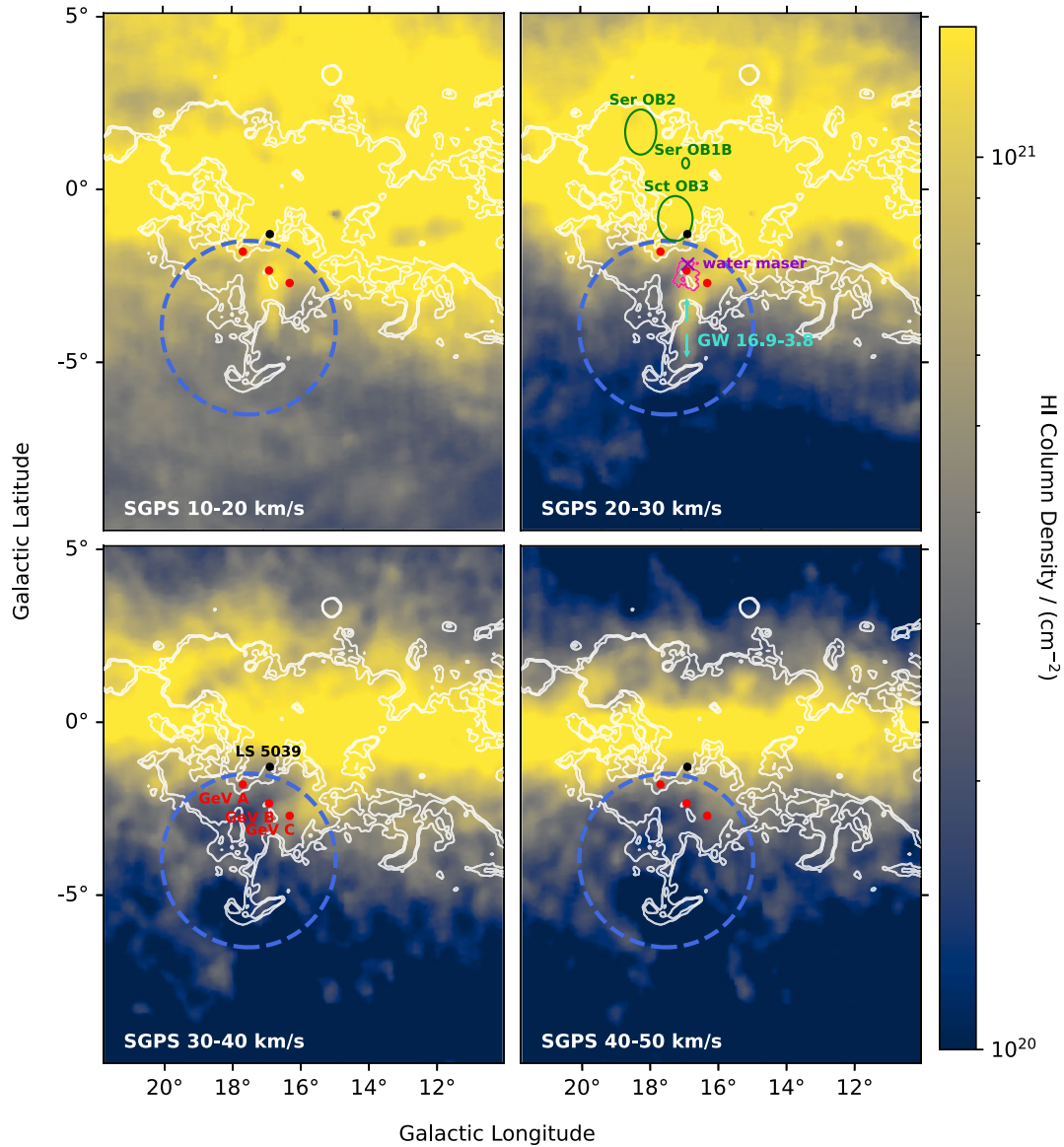
Matsunaga et al. (2001) showed several Galactic supershells emitting  $^{12}\text{CO}$ . Fig. B4 shows the  $^{12}\text{CO}(1-0)$  distributions from the CfA-Chile CO survey. These maps cover an expanded region (down to  $b = -5^\circ$ ) compared to the Nanten  $^{12}\text{CO}(1-0)$  maps

shown by Collins et al. (2021). We used the X-factor  $X_{\text{CO}} = 1.5 \times 10^{20}\ \text{cm}^{-2}/\text{K km s}^{-1}$  from Strong et al. (2004) to convert to a molecular hydrogen column density. We see a molecular cloud feature in the 15–30 km/s range towards the GeV B gamma-ray peak, as pointed out by Araya et al. (2019) and also by Collins et al. (2021), who used higher-resolution Nanten  $^{12}\text{CO}(1-0)$  data (we show the Nanten contours for this molecular feature in Fig. 7). Interestingly in the same velocity range, the water maser G016.8689–02.1552 is found towards this molecular cloud, indicating it is active in star formation (Urquhart et al. 2011; Kalenskii & Shchurov 2016). The maser is likely associated with L379 IRS1, a massive star-formation region located at a distance of 2.5 kpc (Kalenskii & Shchurov 2016).

### 3.6 X-ray observations

Callaway et al. (2000) used the ROSAT PSPC all-sky survey in the 0.1–0.28, 0.4–1.2, and 0.7–2.0 keV energy ranges to investigate the X-ray emission. They suggested that the X-ray emission may originate from hot gas driven by the stellar winds and SNRs that power the Scutum Supershell. Fig. B1 shows wide-scale views of the MAXI SSC 0.7–1.0 keV and ROSAT PSPC 0.4–1.2 keV X-ray photon fluxes. We can see that both datasets reveal X-ray emission peaking locally towards the Scutum Supershell and extending  $\sim 5^\circ$  south of the  $\text{H}\alpha$  feature (black contours).

We broadly replicated the analysis performed by Callaway et al. (2000) in their analysis of the ROSAT PSPC data. We first converted the MAXI SSC and ROSAT PSPC photon flux maps to an absorbed (observed) energy flux via the online Portable, Interactive, Multi-Mission Simulator (PIMMS) tool (Mukai 1993). For this step, we assumed a black-body thermal model (with temperature  $T$ ) for the X-ray emission, and used an upper-temperature limit of  $T = 10^7$  K, similar to Callaway et al. (2000), which is suitable for the production of diffuse soft X-ray emission from thermal plasma processes (Snowden 2004). The PIMMS tool estimates the unabsorbed energy flux by accounting for



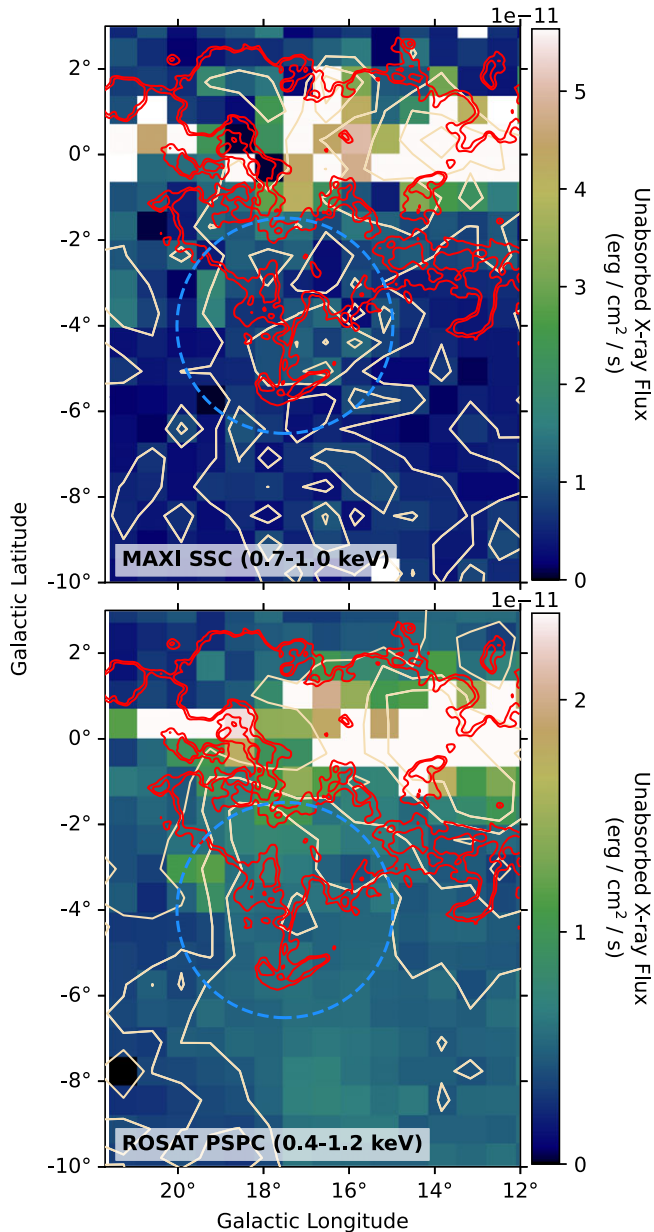
**Figure 7.** SGPS HI column density maps (McClure-Griffiths et al. 2005) for various velocity ranges.  $H\alpha$  emission is indicated as white contours at 40 and 50 Rayleigh (Finkbeiner 2003). The Scutum Supershell is indicated by the blue dashed circle. The *Fermi*-LAT GeV sources (GeV A, B, and C) are marked with red dots (Araya et al. 2019), and the binary LS 5039 with a black dot. The pink contours in the 20–30 km/s map show the molecular hydrogen Nanten CO(1–0) emission (from Mizuno & Fukui 2004 for the (15–30) km/s range). The same velocity range also encompasses the water maser G016.8689–02.1552 (purple cross) (Urquhart et al. 2011). The HI Galactic worm, GW 16.9–3.8, and its orientation are indicated in turquoise, and the green dashed ellipses mark the OB associations Ser OB2, Ser OB1B, and Sct OB3.

photoelectric absorption from the total column density ( $n_H$ ) of the foreground gas from the HI and CO observations (McClure-Griffiths et al. 2005; Dame et al. 2001) integrated over the velocity range from 0 to 30 km/s. The above-mentioned process was repeated on a pixel-by-pixel basis using a 40 arcmin  $\times$  40 arcmin binning (a factor 4 larger than the original MAXI SSC pixels), and the HI and CO data were regridded to match the X-ray data. The unabsorbed fluxes in the soft band are directly compared between MAXI and ROSAT in Fig. 8 in relation to the  $H\alpha$  emission. Figs. B2 and B3 shows the photon fluxes and the absorbed and unabsorbed energy fluxes for both ROSAT PSPC and MAXI SSC observations.

Overall, the MAXI SSC images reveal similar large-scale X-ray structures overlapping the Scutum Supershell to those highlighted by Callaway et al. (2000) using ROSAT data. The X-ray emission appears inside the Scutum Supershell boundary, encompassing the  $H\alpha$  features.

To estimate the X-ray unabsorbed luminosity within the Scutum Supershell, we selected a region identical to Callaway et al. (2000) and used PIMMS to convert the energy flux to a luminosity, after subtracting the X-ray emission from the background regions defined in Table A6 and using the column density from the HI and CO data averaged over the region, and a temperature of  $T = 10^7$  K for the black-body model. We obtained a luminosity  $L_{X-ray}$  from





**Figure 8.** Soft-band X-ray unabsorbed flux maps for both ROSAT PSPC and MAXI SSC. The  $H\alpha$  contours (red) are shown at the 40 R and 50 R levels. X-ray contours (white) are shown at the 5, 10, and 15  $\sigma$  level. The Scutum Supershell boundary is illustrated as a blue dashed circle (Callaway *et al.* 2000).

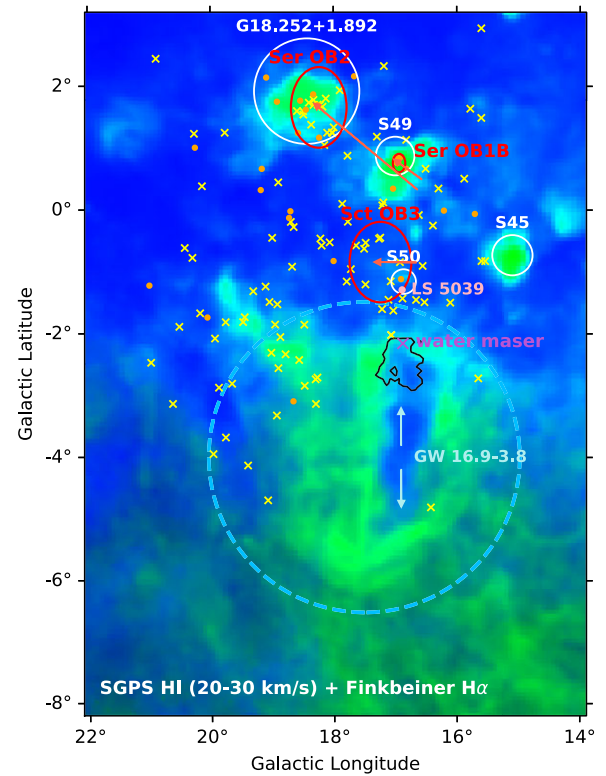
the unabsorbed X-ray emission of

$$L_{X\text{-ray, ROSAT}} = 3.9 \times 10^{36} (d/2.5 \text{ kpc})^2 \text{ erg s}^{-1}$$

for ROSAT PSPC (0.4–1.2 keV) and

$$L_{X\text{-ray, MAXI}} = 4.6 \times 10^{36} (d/2.5 \text{ kpc})^2 \text{ erg s}^{-1}$$

for MAXI SSC (0.7–1.0 keV). For completeness, Table A5 lists the results for different temperatures. We conclude that our PIMMS-derived luminosity is consistent (within 4%) to those obtained by Callaway *et al.* (2000).



**Figure 9.** Composite of  $H\alpha$  emission (green) (Finkbeiner 2003) and HI emission (blue) (McClure-Griffiths *et al.* 2005) integrated over the 20–30 km/s range. The Galactic worm GW 16.9–3.8 is the prominent HI vertical feature seen surrounded by the  $H\alpha$  emission. The CO(1–0) emission (Mizuno & Fukui 2004) for the 15–30 km/s range (black contours) shows the molecular hydrogen encompassing the water maser G016.8689–02.1552 (purple cross) (Urquhart *et al.* 2011). The proper motions (red arrows) of the star clusters linked to the OB associations (Ser OB2, Ser OB1B, Sct OB3; red ellipses) indicate their location 1 Myr ago (Table A3). White circles mark HII regions (Anderson *et al.* 2014) with velocities 15–30 km/s and radius of >500 arcsec. Stars confirmed as O-type (orange dots) and those catalogued as OB (uncertain O or B; yellow crosses) (Reed 2003) were considered in the photo-ionisation calculations. LS 5039 (pink dot) is a high-mass X-ray binary.

#### 4. Discussion

We will now review the multi-wavelength emissions towards the Scutum Supershell and discuss the potential origins of the  $H\alpha$  spine and bow-shock features.

The X-ray maps from MAXI SSC exhibit comparable morphology and fluxes to the ROSAT PCPS observations (compare Table A5 and Callaway *et al.* 2000). Our analysis with PIMMS indicates that the soft-band luminosity of both the MAXI SSC and ROSAT PSPC X-ray emissions is approximately  $10^{36} (d/2.5 \text{ kpc})^2 \text{ erg s}^{-1}$ . Morphologically, the thermal soft-band X-ray emission (see Fig. 8), which is present in the Scutum Supershell and extends further south, indicates the presence of hot gas (as also noted by Callaway *et al.* 2000).

The SGPS HI observations reveal a broadly similar morphology to those observed by Callaway *et al.* (2000) using earlier NRAO (VLA) HI data. However, closer inspection of the SGPS HI image in the 20–30 km/s range, compared to the  $H\alpha$  emission reveals a spatial anti-alignment of the spine with the Galactic worm GW 16.9–3.8 seen in HI (see Fig. 9). GW 16.9–3.8 was first discussed by Callaway *et al.* (2000) and Koo *et al.* (1992) as potentially having some relation to the Scutum Supershell. The Galactic worm

**Table 2.** Expected  $H\alpha$  luminosity  $L_{\text{exp}}$  created by Lyman continuum photons from the OB associations Ser OB1B, Ser OB2, and Sct OB3 as sources of photo-ionisation. The luminosities are estimated for the bow-shock region (dotted rectangle in Fig. A1). The surface brightness  $S$  and corresponding surface area  $A$  are used to estimate the absorption photon rate  $Q_{\text{env}}$ . The number of stars (# Stars) in each OB association is taken from Stoop et al. (2023), Dib, Schmeja, & Parker (2018), the number of O-type stars from Mel'Nik & Efremov (1995), Stoop et al. (2023), and the remaining stars are considered B-type stars. These numbers are used together with photon rates for individual stars of a specific spectral type from Vacca, Garmany, & Shull (1996) to calculate the photon rate  $Q_*$ .

Name	Dist. (kpc)	# Stars		$Q_*$ ( $10^{50}$ /s)	$S$ (Rayl.)	$A$ ( $\text{pc}^2$ )	$Q_{\text{env}}$ ( $10^{48}$ /s)	$r_{d=2.5\text{kpc}}$ (pc)	$L_{\text{exp},d=2.5\text{kpc}}$ ( $\text{erg s}^{-1}$ )	$r_{d=1.5\text{kpc}}$ (pc)	$L_{\text{exp},d=1.5\text{kpc}}$ ( $\text{erg s}^{-1}$ )
		O-type	B-type								
Ser OB1B	1.71 <sup>a</sup>	19 <sup>a</sup>	118 <sup>a</sup>	11.3	1 702	42	2.4	826	$3.4 \times 10^{36}$	270	$8.6 \times 10^{36}$
Ser OB2	1.60 <sup>b</sup>	8 <sup>c</sup>	252 <sup>d</sup>	5.4	233	719	5.7	935	$1.4 \times 10^{36}$	219	$5.6 \times 10^{36}$
Sct OB3	1.33 <sup>b</sup>	2 <sup>c</sup>	143 <sup>d</sup>	2.0	65	550	1.2	1179	$0.4 \times 10^{36}$	205	$2.3 \times 10^{36}$

<sup>a</sup>Stoop et al. (2023).

<sup>b</sup>Wright (2020).

<sup>c</sup>Mel'Nik & Efremov (1995).

<sup>d</sup>Dib et al. (2018): Total number of stars of any spectral type.

overlaps a void in the  $H\alpha$  emission, and as a result, it is either shielding the region behind it from ionising radiation. Thereby preventing  $H\alpha$  emission, or the  $H\alpha$  emission behind absorbed by HI and dust in front, making it invisible to our observations. The spine feature may therefore represent the ionised surface of the Galactic worm GW 16.9–3.8. The northern edge of the worm hosts a molecular gas component based on  $^{12}\text{CO}$  emission in an overlapping velocity range (15–30 km/s) from Nanten observations, and a water maser G016.8689–02.1552 (Urquhart et al. 2011; Heiles, Reach, & Koo 1996), suggesting the presence of active star formation.

Fig. 9 also shows the location of O and OB stars in the distance range of 1–3 kpc, along with the OB associations Ser OB1B, Ser OB2, and Sct OB3. These three OB associations have recent distance estimates of 1.3–1.7 kpc (see Table 2), based on Gaia DR3 measurements. The star clusters associated with the OB associations all have proper motions in the range 0.2–7 mas yr<sup>-1</sup> (Table A3), which means they have travelled  $\sim 1^\circ$  or more over their life times. It should be noted that Ser OB1B has been linked to GW 16.9-3.8 and two other Galactic worms GW 14.9-1.6 and GW 19.5-6.4 (Koo et al. 1992). GW 16.9-3.8 is centred at a velocity of 25 km/s, giving a near distance solution of 2.5 kpc using the Galactic rotation model of Brand & Blitz (1993). The somewhat lower GAIA-derived distance for Ser OB1B might suggest the local velocity of GW 14.9-1.6 is influenced by the expansion of the Scutum Supershell by 10 km/s or so.

Interestingly, the  $H\alpha$  bow-shock feature corresponds to a peak in the [S II] emission towards its rightmost edges according to our Skywatcher observations (see Fig. 4). At the rightmost edge there is also overlapping 4.85 GHz radio continuum emission (see Fig. 5), and overlapping infrared emission at 60 and 100  $\mu\text{m}$  (see Fig. 6). The  $H\alpha$  spine has some overlapping [S II] emission but at a weaker level than for the bow-shock region. No other obvious overlapping radio or infrared emission is seen.

Overall, given the presence of many potential stellar and non-stellar sources of ionisation in the region, we will consider both photo-ionisation and shock-induced excitation processes for both the spine and the bow-shock  $H\alpha$  emission features.

#### 4.1 Photo-ionisation excitation

Here, we will consider the possibility of Lyman continuum (LyC) photons as a source of ionisation for the  $H\alpha$  emission. The LyC photons could arise from O and B stars from within the OB associations or from additional O and B stars from a wider region.

We employed the method from Dennison et al. (1997), which calculates the expected luminosity of  $H\alpha$  emission created by LyC photons some distance away. Some of the LyC photons will be absorbed via photoionisation. Subsequent a recombination to produce  $H\alpha$  emission in surrounding compact HII regions or in broader regions farther out. We can compare this expectation to the observed  $H\alpha$  luminosity from the bow-shock region which is

$$L_{\text{obs},H\alpha} \sim 2 \times 10^{36} (d/2.5 \text{ kpc})^2 \text{ erg s}^{-1}.$$

By rearranging Eq. 1 of Dennison et al. (1997) and transforming to luminosities, the expected luminosity  $L_{\text{exp},H\alpha}$  of the  $H\alpha$  emission from a region of distance  $d$  from Earth, and with solid angle  $\Omega$ , thickness  $s$  and distance  $r$  from a LyC photon source is calculated via:

$$L_{\text{exp},H\alpha} = \frac{4\pi d^2 \Omega (Q_*/4\pi - Q_{\text{env}}/4\pi)}{r^2 \alpha_B(T) (1 + 2r/s)^{-0.5} (T/10^4 \text{ K})^{0.9}} \times \frac{\text{erg/s/cm}^2/\text{arcsec}^2}{4.858 \times 10^{17} \text{ pc/cm}^6}. \quad (1)$$

$Q_*$  is the LyC photon rate for the stellar source in question, either a grouping of stars or an individual star. We obtained  $Q_*$  by summing over individual photon rates, which we obtained from Vacca et al. (1996) for individual O and B stars dependent on their spectral type.  $Q_{\text{env}}$  is the effective absorption LyC photon rate required to match the observed  $H\alpha$  surface brightness  $S$  assumed to be due to recombination from the ‘environment’ (env), a region surrounding the photon source, or, a region in between the photon source and the region of interest. Here, we calculate this rate based on the surface area  $A$  and  $H\alpha$  surface brightness  $S$  of the surrounding region.

$$Q_{\text{env}} = 2.75 \frac{\text{pc}}{\text{cm}^6} \frac{S}{\text{Rayleigh}} \left( \frac{T}{10^4 \text{ K}} \right)^{0.9} A \alpha_A(T). \quad (2)$$

As per Dennison et al. (1997), we assume an edge-brightened shell geometry for the region of interest (the bow-shock). The recombination rates  $\alpha_A = 4.18 \times 10^{-13}$  and  $\alpha_B = 2.59 \times 10^{-13} \text{ cm}^3/\text{s}$  are taken from Osterbrock (1989) for  $T = 10^4 \text{ K}$ .

We first calculated the expected  $H\alpha$  luminosities for the three OB associations as the sources of LyC photons, and the bow-shock region with thickness of  $s = d \cdot \tan(0.8^\circ)$  (the extension of the rectangular bow-shock region in North-South direction), centred at  $l = 17.3^\circ$  and  $b = -5.5^\circ$  (this region is shown in Fig. A1), and assuming a distance of  $d = 2.5 \text{ kpc}$ . Ser OB1B and the HII region Messier 16 (S49) are related to the star cluster NGC 6611 (Bally

& Chia 2019) which contains 51 stars (Dib et al. 2018). Recent work by Stoop et al. (2023) states that NGC 6611 hosts 19 O-type stars (with different provided spectral subclasses) and 137 stars in total at a distance of 1.706 kpc, based on *Gaia* EDR3. Here, we will assume the remaining 118 stars are early B-type stars. For Ser OB2, Forbes (2000) suggested a relationship to the HII region Sh2-54 (G018.252+1.892), and the star cluster NGC 6604. Ser OB2 and its star cluster NGC 6604 contain 260 stars (Dib et al. 2018), eight of which are O-type stars (Mel’Nik & Efremov 1995). The remaining 252 stars will be assumed to be B-type stars. Sct OB3 contains 145 stars (Dib et al. 2018), two of which are O-type stars as noted by Mel’Nik & Efremov (1995). The Wolf-Rayet star WR 115 is another member of Sct OB3. We will assume the remaining 143 stars are B-type. The resulting  $Q_*$  for the above assumptions are listed in Table 2. The number of stars belonging to the OB associations and the corresponding spectral subtypes, together with the assumption that the remaining stars are B-type stars introduce some uncertainty. If we only include the O stars in the calculation of the photon rate  $Q_*$ , we obtain  $2.9 \times 10^{50}/s$  for Ser OB2,  $0.6 \times 10^{50}/s$  for Sct OB3, and  $10.1 \times 10^{50}/s$  for Ser OB1B. To estimate  $Q_{env}$ , we extracted the  $H\alpha$  surface brightness from the elliptical extensions of the OB associations (see Fig. 9 and Table A3). This value depends on the choice of the extraction region and increased to  $\sim 8 \times 10^{48}/s$  for Ser OB2 when increasing the extraction region to encompass the bright  $H\alpha$  emission in that region, varied between  $(1.0 - 1.5) \times 10^{48}/s$  for Sct OB3 when varying the ellipticity of the extraction region, and increased to  $\sim (10 - 13) \times 10^{48}/s$  for Ser OB1B when increasing the region to encompass the bright  $H\alpha$  emission. The results in Table 2 show that the expected  $H\alpha$  luminosity from each of the OB associations  $L_{exp,H\alpha}$  matches that of the observed luminosity of  $\sim 2 \times 10^{36} (d/2.5 \text{ kpc})^2 \text{ erg s}^{-1}$  for the bow-shock region. Using the decreased  $Q_*$  and the increased  $Q_{env}$ , we obtain luminosities  $L_{exp,d=2.5kpc}$  of  $0.7 \times 10^{36} \text{ erg/s}$  for Ser OB2,  $0.1 \times 10^{36} \text{ erg/s}$  for Sct OB3, and  $3.0 \times 10^{36} \text{ erg/s}$  for Ser OB1B. If instead we assume the  $H\alpha$  features are at a distance  $d = 1.5 \text{ kpc}$  (and adjust  $r$  and  $s$  accordingly) to match the GAIA-derived distances of the OB associations, the expected luminosity  $L_{exp,1.5}$  increase. We conclude that the OB associations could be photo-ionisation sources of the observed  $H\alpha$  features.

In the second application of Equation (1), we assume the LyC photons are produced from massive stars specifically catalogued across the field extending beyond the three OB associations. We used the Reed (2003) catalogue and Simbad (Wenger et al. 2000) to identify O and OB stars within 1 to 3 kpc distance from Earth, and Galactic coordinates  $15.5^\circ \leq l \leq 21^\circ$  and  $-5^\circ \leq b \leq 5^\circ$ . We found a total of 33 O stars with identified spectral sub-types, and an additional 103 stars listed as ‘OB’ without spectral sub-types. The O and OB stars in the field of the Scutum Supershell are shown in Fig. 9 with the full lists given in Tables C2 and C3. Here, we will assume a photon rate  $Q_*$  of  $10^{49}/s$  for stars labelled ‘OB’, corresponding to the rate of stars with a spectral type O9. For the absorption rate  $Q_{env}$ , we choose circular regions of radius  $0.2^\circ$  around each star to extract the surface brightness and area. The resulting values range from  $(0.3 - 50) \times 10^{47}/s$ . For comparison, we also extracted the (cumulative) photon rate from a larger region further away from the Galactic plane (see Fig. A1) and obtained a value of  $2.5 \times 10^{48}/s$ . The resulting expected luminosities range from  $10^{34}$  to  $10^{35} \text{ erg/s}$  for individual stars. For each of the different star groups (O stars only, OB stars only, and both O and OB

**Table 3.** Expected  $H\alpha$  luminosity  $L_{exp}$  estimated at the bow-shock region (solid orange box in Fig. A1) using Equation (1) assuming nearby O and OB stars as photo-ionisation sources. The details of these stars are taken from Reed (2003) and Simbad (Wenger et al. 2000) and are limited to the region between  $15.5^\circ \leq l \leq 21^\circ$  and  $-5^\circ \leq b \leq 5^\circ$  and distances 1–3 kpc. Results are also listed for two additional O stars south of the bow-shock, HD 175754 (O8 II(f)) and HD 175876 (O6.5 III(n)(f)) (red circles in Fig. A1). Details of the stars are listed in Table C2 and C3.

Star Grouping	# Stars	$L_{exp,d=2.5kpc}$ ( $\text{erg s}^{-1}$ )
O stars	33	$7.2 \times 10^{36}$
OB stars	103	$7.2 \times 10^{36}$
O+OB stars	136	$14.4 \times 10^{36}$
HD 175754	1	$0.4 \times 10^{36}$
HD 175876	1	$1.3 \times 10^{36}$

stars), we obtain luminosities of  $\sim 10^{37} \text{ erg/s}$  (see Table 3 for the results of the different star groupings).

Additionally, we calculate the expected luminosity with the two O-type stars HD 175754 and HD 175876 as LyC photon sources. They are found about  $5^\circ$  south of the Scutum Supershell (see Fig. A1) and were highlighted by Callaway et al. (2000) as potentially influencing the dynamics of the region. In this case,  $Q_{env}$  is taken again from a circular region of radius  $0.2^\circ$ . For both stars,  $Q_{env}$  is  $\sim 6 \times 10^{46}/s$  using this method, while extracting it from a larger region between the stars and the bow-shock leads to rates of  $\sim 2 \times 10^{48}/s$ . The corresponding luminosities only vary slightly between these two methods and are listed in Table 3.

The expected  $H\alpha$  luminosities  $L_{exp}$  for the various stars and star groupings are given in Table 3. For the O- and OB-star groupings,  $L_{exp}$  easily matches the measured  $H\alpha$  luminosity of the bow-shock region. Similarly, ionisation from the two O stars HD 175754 and HD 175876 further south individually could also play a role. Overall, photo-ionisation driven by the O and OB<sup>4</sup> stars present in OB associations or from individual stars around the field likely provide the bulk of the excitation energy for the  $H\alpha$  bow-shock emission. For the  $H\alpha$  spine feature, which is even closer to these stars by about 100 pc, the role of photo-ionisation would likely be dominant. Such a conclusion is further supported by the placement of the Galactic worm GW 16.9–3.8, which runs along the spine, with the neutral hydrogen seen to the right of the spine, and the ionising sources on the left. In this scenario, the spine forms the ionised surface of the worm.

Note that we have neglected reddening in our measured  $H\alpha$  luminosities and in determining  $Q_{env}$  in the above calculations. Using the Galactic Dust Reddening and Extinction online tool<sup>c</sup> (Schlafly & Finkbeiner 2011; Schlegel, Finkbeiner, & Davis 1998), we determined an extinction level of  $A_v = (1.26 \pm 0.09) \text{ mag}$  in the bow-shock region, increasing to about 2 mag towards the top end of the spine. However, this converts to an extinction at  $H\alpha$ ,  $A_{H\alpha} = \sim 0.4 \text{ mag}$ , resulting in an overall increase in luminosity of

<sup>4</sup>Due to varied classification criteria, the exact type O or B is not precisely known (Reed 2003).

<sup>c</sup><https://irsa.ipac.caltech.edu/applications/DUST/>.



only 40%. This also applies to  $Q_{\text{env}}$ . Since  $Q_{\text{env}}$  is somewhat negligible compared to  $Q_*$  for larger groups of stars, and so our overall conclusions remain unchanged.

#### 4.2 Excitation from collision and/or shocks

Photo-ionisation appears to be an important excitation mechanism for the  $H\alpha$  spine and the bow-shock feature. However, given the interesting morphology of the bow-shock and its multi-wavelength counterparts, we will explore the potential role of alternative or additional excitation via shocks or collisions.

A number of studies have noted that a combination of  $H\alpha$ , [S II], radio continuum, and infrared continuum can be used to help determine the  $H\alpha$  excitation processes, and important in classifying emissions from SNRs, planetary nebulae, and HII regions (e.g. Dwek & Arendt 1992; Sabbadin, Minello, & Bianchini 1977; Braun & Walterbos 1993). Radio continuum emission at levels of 0.001 to 0.7 Jy/beam, together with  $H\alpha$  emission, are used by Stupar et al. (2008) as an indicator of shock heating from SNRs. A study by Arendt (1989), Saken et al. (1992) points out that certain infrared colour ratios may indicate the origin of excitation, such as from supernova remnants (SNRs), planetary nebulae, and HII regions.

Interestingly, for the right side of the bow-shock, we find infrared colour ratios for  $25 \mu\text{m}/60 \mu\text{m}$  ( $\lesssim 0.1$ ) and  $60 \mu\text{m}/100 \mu\text{m}$  ( $\sim 0.3$ ) that appear to be consistent with those found for old ( $> 10^4$  yr) SNRs similar to those of SNR G205.5+0.5 and others (see Table 2 Saken et al. 1992) and also with HII regions, as shown by Arendt (1989). On the other hand, we find no overlapping catalogued HII regions (Anderson et al. 2014). Moreover, we find for this region a peak in [S II] emission (Fig. 4),  $H\alpha$  emission (Fig. 2), and overlapping radio continuum (Fig. 5). Overall, the combination of these multi-wavelength features might suggest some contribution from shock heating.

Some further insight into the potential for shock-related influences may come from the recent work of Drozdov et al. (2022), who conducted a 3D hydrodynamic simulation to study the evolution of supernova (SN) explosions in OB associations based on a model by Vasiliev (2013), which did not consider stellar photoionisation and stellar winds. They propose OB associations and their SN explosions as driving mechanisms for large-scale outflow-driven  $H\alpha$  emission (see their Figure 9). They examined three OB association models: one positioned at the Galactic midplane and the other two positioned at heights of 20 and 60 pc above the Galactic plane. The ages of the OB associations for the three models varied between 10 and 20 Myr. SN events within the OB association, which release approximately  $10^{51}$  erg every 1–2 Myr, can result in outflows observable in  $H\alpha$  and X-rays (0.7–1.2 keV). In one case, for OB associations 20 pc above the plane and 16 Myr after the first SN, their predicted  $H\alpha$  emission resembles the features we observe and includes quite distinctive central outflow and bow-shock features exceeding surface brightness levels of 100 R. Similar features are predicted for the HI emission. For OB associations modelled further (60 pc) from the plane, features resembling a blow out are predicted for the  $H\alpha$  and the HI emissions.

Ser OB1B is associated with the massive star cluster NGC 6611, which includes two populations of stars – a young population with an age of 1.3 Myr and an old population with an age of 7.5 Myr (with almost all OB stars belonging to the young population) (Stoop et al. 2023). It is located  $\sim 10$  pc ( $0.3^\circ$ ) above the Galactic plane. Ser OB2, with an age of 7.8 Myr (Dib et al. 2018), is located

$\sim 40$  pc ( $1.5^\circ$ ) above the Galactic plane. Sct OB3 is still young with an age of 1.3 Myr (Dib et al. 2018) and is located approximately 15 pc ( $0.6^\circ$ ) below the Galactic plane. All three OB associations have at some point in the past  $\sim 1$  Myr been positionally aligned with an elongation of the  $H\alpha$  spine, according to their proper motions (see Fig. 9). These OB associations are key sources of energy that stimulate  $H\alpha$  emission, through SNe, stellar winds, and photoionisation.

As discussed earlier, SNR G18.7–2.2 (potentially linked to HESS J1825–137) and the energetic pulsar PSR J1826–1334, are both likely at a distance of 4 kpc or greater. The energetic but radio-quiet pulsar PSR J1826–1256, linked to HESS J1826–130, has a distance estimate of  $\sim 3.5$  kpc (Karpova, Zyuzin, & Shibano 2019). The other SNRs catalogued from Green (2019) all have likely distances of  $> 4$  kpc, given their small radio diameters. Additionally, we find no other pulsars with distances  $< 3$  kpc within the region (Manchester et al. 2005).

Moldón et al. (2012) suggested that the high-mass X-ray binary LS 5039, also known as the gamma-ray binary HESS J1826–148, originated within Sct OB3. LS 5039 is at a distance of  $(2.0 \pm 0.2)$  kpc (Marcote et al. 2015; Aharonian et al. 2005, 2006) and hosts a neutron star with a possibly high magnetic field of  $\sim 10^{11}$  T, based on a 9 s X-ray periodicity observed by Yoneda et al. (2020) and Makishima et al. (2023). This would classify the neutron star as a magnetar, but the 9 s periodicity has been questioned by Volkov et al. (2021) and Kargaltsev et al. (2023). Magnetars have been linked to unusually energetic hypernovae (e.g. Duncan & Thompson 1992) that may generate asymmetric outflows (such as in long gamma-ray bursts). Given the links to hypernovae, and the rarity of magnetars in the Milky Way (only 30 are currently catalogued Olausen & Kaspi 2014), LS 5039 might be an interesting, although speculative, contributor to the dynamics of the Scutum Supershell and associated  $H\alpha$  emission. The  $H\alpha$  luminosities of the spine and bow-shock are in fact several orders of magnitude larger than those seen arising in collisional or shock-driven scenarios, such as protostellar jets, and somewhat similar to those found in the black-hole X-ray binary Cyg X-1 and the unique SS-433 micro-quasar system (see Table A2 where we compare these luminosities). In this scenario, the spine morphology may be influenced by such an outflow. However, as discussed earlier, it appears more likely to be guided by the Galactic worm in HI emission (and thus photo-ionisation).

## 5. Conclusions

This work has focused on the  $H\alpha$  spectral line emission towards the Scutum Supershell that was first studied by Callaway et al. (2000) using the WHAM survey with a  $\sim 1^\circ$  angular resolution. Towards this region, there are several OB associations, numerous catalogued O-type stars, supernova remnants, PWN and a high-mass X-ray binary LS 5039, that could drive the excitation responsible for the  $H\alpha$  emission.

Based on recent  $H\alpha$  maps from Finkbeiner (2003), the SuperCOSMOS  $H\alpha$  Survey (SHS) (Parker et al. 2005) and our own observations (with a Skywatcher Evolux 62ED refractor telescope), all with arc-second to arc-minute angular resolution, we identify  $H\alpha$  emission features, resembling a long spine and a bow-shock that each extend over several degrees in length. Our spectral analysis of the  $H\alpha$  data from WHAM suggests that these features have a kinematic distance in the range from 2 to 3 kpc.

These multi-wavelength observations, alongside the presence of OB associations, indicate significant energetic processes in the

region. Our observations revealed that areas within the bow-shock with the brightest H $\alpha$  emission also displayed [S II] emission. Additionally, the same region exhibits continuum radio emission at 4.85 GHz, as well as infrared emission at 60 and 100  $\mu\text{m}$ . These findings could indicate the influence of shock heated gas in shaping the characteristics of the bow-shock.

We also examined HI data from the SGPS and found broadly similar blowout features consistent with those found by Callaway et al. (2000) in earlier HI data. Moreover, a comparison of the H $\alpha$  data with the SGPS HI data cube, integrated over the 20 to 30  $\text{km s}^{-1}$  range (2–3 kpc distance), reveals a clear void in the H $\alpha$  emission overlapping the Galactic worm GW 16.9–3.8 HI emission running along a North-South direction adjacent to the spine. Thus, the Galactic worm appears to be playing a physical role in shaping the morphology of the H $\alpha$  spine.

Our analysis of recent MAXI SSC X-ray emission in the soft (0.7–1.0 keV) band revealed a similar picture as shown by Callaway et al. (2000) using ROSAT PSPC data in the (0.4–1.2 keV) range. The X-ray emission is found inside the boundary of the Scutum Supershell and partly overlaps the H $\alpha$  features. The X-ray emission in a wider field ( $40^\circ \times 40^\circ$ ) reveals several X-ray peaks further to the Galactic-south, which may be connected with larger-scale Galactic diffuse X-ray emission. Overall, the X-ray emission is consistent with hot gas over large regions of the Scutum Supershell.

We considered both photo-ionisation and shock-heating as sources of excitation for the H $\alpha$  emission. Following the method of Dennison et al. (1997), we estimated the H $\alpha$  luminosity via Lyman continuum photons from O- and B-type stars associated with the three nearby OB associations (Ser OB1B, Ser OB2 and Sct OB3), and additional O- and B-type stars from a wider region. Assuming a distance of 2.5 kpc for the H $\alpha$  features, the OB associations and/or the wider grouping of O and B stars could provide sufficient excitation for photo-ionisation to match the measured H $\alpha$  luminosity (few  $10^{36}$   $\text{erg s}^{-1}$ ). If the H $\alpha$  spine and bow-shock features are located at the same 1.5 kpc distance as determined for the OB association distances (1.3–1.7 kpc; based on GAIA data), the predicted photo-ionisation luminosity from the OB associations increases by a factor 3–6, further boosting this interpretation.

For the bow-shock H $\alpha$  feature however, its overlap with optical [S II] and continuum emission in the radio and infrared bands could suggest some additional shock-induced excitation or heating. Due to the lack of an absolute flux calibration for our [S II] image, we cannot presently determine the [S II]/H $\alpha$  ratio, an important diagnostic of the potential for shock-induced excitation. Future work will include an accurate determination of the [SII]/H $\alpha$  ratio using WiFes (Dopita et al. 2007) spectroscopic observations towards the bow-shock and spine regions.

Recent MHD simulations by Drozdov et al. (2022) demonstrate the potential for supernova events to drive outflow and bow-shock types of features of the same energetic nature and physical scale as the H $\alpha$  emission we observe here. The nearby  $\gamma$ -ray sources HESS J1825–137 and HESS J1826–130 are at distances 4 kpc and so are likely to be unrelated. However, the high-mass X-ray binary LS 5039 (at 2 kpc distance, and linked to Sct OB3) has been suggested to host a magnetar that could have been produced in a hypernova event with outflows (akin to a long gamma-ray burst). We could speculate that such a hypernova outflows might have influenced the dynamics of the H $\alpha$  emission, although it is clear, from our calculations, that photo-ionisation plays an important role.

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## A. Data Analysis

### A.1 H $\alpha$ Emission

To calculate the H $\alpha$  luminosities  $L_{\text{H}\alpha}$  of the bow-shock and spine features reported in Subsection 3.1, we extracted intensities from regions surrounding them and from regions to estimate the corresponding background to be subtracted. These regions are defined in Table A1 and illustrated in Fig. A1. The table also provides the resulting luminosities, extracted from both Finkbeiner and WHAM maps. Comparisons to luminosities of other sources are listed in Table A2.

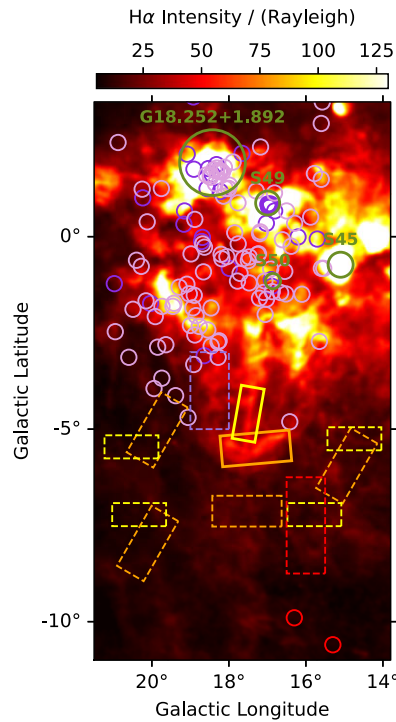
We compared our obtained H $\alpha$  luminosities Table A1 to the ones of other sources Table A2.

In Subsection 4.1 we performed a dedicated analyses of photo-ionisation from OB associations in the region. Table A3 provides

**Table A1.** Definition of rectangular regions and resulting H $\alpha$  luminosities ( $L_{\text{H}\alpha}$ ) for Finkbeiner and WHAM surveys. These results were used in Subsection 3.1. Signal regions are highlighted in bold, while the remaining ones are background regions. The rectangle is defined with width  $w$  in North-South and height  $h$  in East-West direction if the angle  $\theta$  is 0. Galactic longitude and latitude are  $l$  and  $b$ .

$l$ (deg)	$b$ (deg)	$w$ (deg)	$h$ (deg)	$\theta$ (deg)	$L_{\text{H}\alpha, \text{Finkb.}}$ ( $10^{36} \text{ erg s}^{-1}$ )	$L_{\text{H}\alpha, \text{WHAM}}$ ( $10^{36} \text{ erg s}^{-1}$ )
Bow shock						
<b>17.30</b>	<b>-5.50</b>	<b>0.8</b>	<b>1.8</b>	<b>5</b>	<b>3.18</b>	<b>2.42</b>
17.53	-7.13	0.8	1.8	0	1.31	1.30
14.94	-5.95	0.8	1.8	60	1.39	1.29
19.86	-5.02	0.8	1.8	60	0.92	1.01
20.11	-7.97	0.8	1.8	60	0.84	0.85
Spine						
<b>17.50</b>	<b>-4.60</b>	<b>0.6</b>	<b>1.4</b>	<b>80</b>	<b>1.86</b>	<b>1.41</b>
14.74	-5.25	0.6	1.4	0	0.80	0.81
15.78	-7.22	0.6	1.4	0	0.72	0.74
20.53	-5.46	0.6	1.4	0	0.48	0.50
20.33	-7.22	0.6	1.4	0	0.50	0.48





**Figure A1.** Illustration of several regions used throughout our analyses to extract  $H\alpha$  intensities from Finkbeiner (2003) and WHAM. The rectangular regions (corresponding to Table A1) include the spine (solid yellow) and the bow-shock (solid orange) features and their corresponding backgrounds (dashed). The purple regions (circles and rectangle) were used to extract the photon rates  $Q_{\text{env}}$  in Equation (1) for O stars (dark purple) and OB stars (light purple), and the red regions (circles and rectangle) for the two HD stars. The HII regions are shown as well.

a list of all OB associations (Wright 2020) towards the Scutum Supershell, together with their associated star clusters (references in table).

## A.2 $H\alpha$ Spectra

We used the GaussPy+ package (Riener *et al.* 2019; Lindner *et al.* 2015) to decompose the components of the WHAM  $H\alpha$  spectra for the region shown in Fig. 2. The resulting Gaussian components for the eight spectra shown in Fig. 2 are shown in Fig. A2. In our case, the GaussPy+ procedure decomposed each pixel's spectrum into typically five to six Gaussian components with one to two clearly dominant ones. In the GaussPy+ process, we trained the smoothing parameter  $\alpha$  using a wide region with boundaries  $b = -8^\circ$  to  $8^\circ$  and  $l = 10^\circ$  to  $24^\circ$ . We trained with 250 spectra, resulting in an  $\alpha$  value of 4.68. Due to the spectral resolution of WHAM, we have set a minimum FWHM of 12 km/s (6 channels) for each Gaussian component.

## A.3 Infrared Emission

The IRIS infrared (IR) emission from Miville-Deschênes & Lagache (2005) shows significant emission in the  $60\mu\text{m}$  and  $100\mu\text{m}$  images towards the right bow-shock region. We estimated the IR flux in these two wavelengths in Subsection 3.4.

**Table A2.**  $H\alpha$  luminosities ( $L_{H\alpha}$ ) of various sources as comparison to the ones of the spine and bow-shock features.

Object	Luminosity ( $\text{erg s}^{-1}$ )	Ref.
M82 halo	$10^{40}$	Shopbell & Bland-Hawthorn (1998)
SS 433	$< 10^{39}$	Panferov, Fabrika, & Bychkova (1993)
Cygnus X-1	$6 \times 10^{34}$	Russell <i>et al.</i> (2007)
HH34	$10^{31}$	Buehrke, Mundt, & Ray (1988)

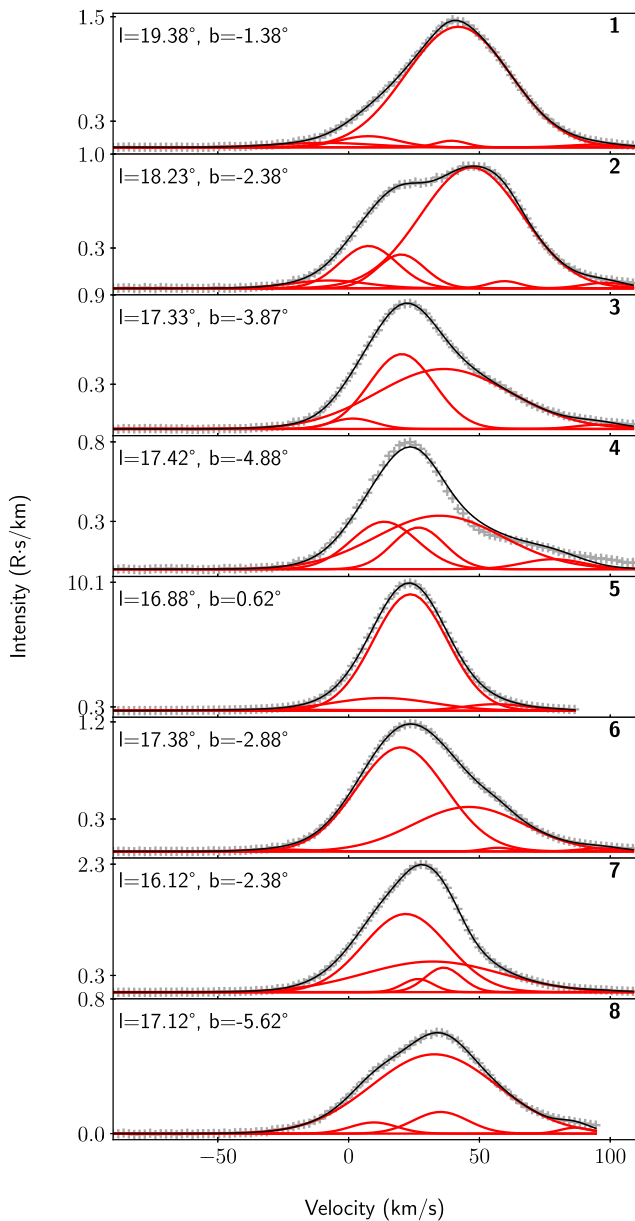
The corresponding region together with the regions used as background estimates are listed in Table A4 (and illustrated in Fig. A3), together with the obtained fluxes.

## A.4 X-ray Emission

To calculate the X-ray luminosity similarly to Callaway *et al.* (2000) shown in Table A5, we used the region at Galactic longitude of  $17.1^\circ$  and latitude of  $-3.5^\circ$  to find the X-ray counts and average total column density. We subtracted the background counts from the region of interest using the rectangular background regions listed in Table A6.

**Table A3.** OB associations Galactic longitude and latitude are  $l$  and  $b$ , respectively. Diameters are represented  $dl$  and  $db$  are from Mel’Nik & Efremov (1995). Star clusters associated with OB associations are taken from Wright (2020). Individual star cluster data include age, proper motions in right ascension  $PM_{ra}$ , and declination  $PM_{dec}$ , along with their references.

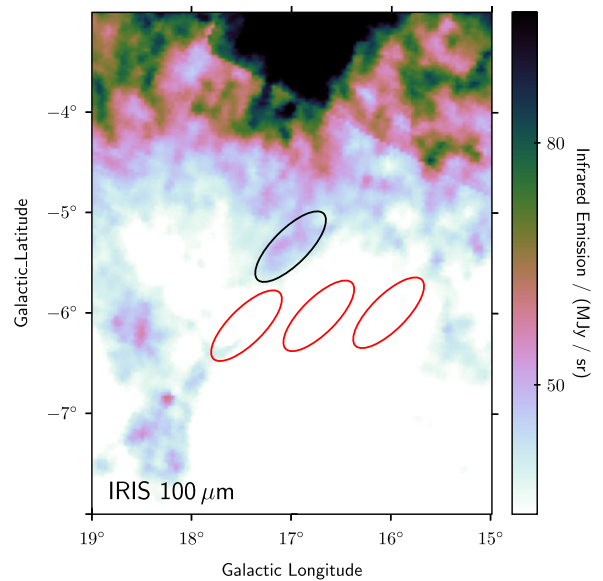
Name	$l$ (deg)	$b$ (deg)	$dl$ (deg)	$db$ (deg)	Star cluster	Age (Myr)	$PM_{ra}$ (mas yr <sup>-1</sup> )	$PM_{dec}$ (mas yr <sup>-1</sup> )	Ref.
Ser OB1B	16.93	0.76	0.2	0.3	NGC 6611	1.3 (7.5)	0.21	-1.59	Stoop et al. (2023)
Ser OB2	18.23	1.66	0.9	1.3	NGC 6604	7.8	1.54	-7.31	Loktin & Popova (2017)
Sct OB3	17.23	-0.84	1.0	1.3	Sct OB3	1.3	-0.98	-1.84	Kharchenko et al. (2013)



**Figure A2.** WHAM  $H\alpha$  spectra from Reynolds et al. (1998) for the eight pixels shown in Fig. 2. The individual Gaussian components (derived with GaussPy+) are shown in red and the total in black.

**Table A4.** IRIS infrared fluxes  $F_{\mu m}$  for different regions (bold refers to the bow-shock region). The ellipse is defined with diameter  $w$  of horizontal axis, diameter  $h$  of vertical axis, and rotation angle  $\rho$  (anti-clockwise). Galactic longitude and latitude are  $l$  and  $b$ .

$l$ (deg)	$b$ (deg)	$w$ (deg)	$h$ (deg)	$\rho$ (deg)	$F_{100}$ (Jy)	$F_{60}$ (Jy)	$F_{25}$ (Jy)
<b>17.00</b>	<b>-5.34</b>	<b>0.35</b>	<b>0.93</b>	<b>45</b>	<b>171</b>	<b>56.7</b>	<b>8.1</b>
16.02	-5.99	0.35	0.93	45	115	33.6	7.2
16.72	-6.02	0.35	0.93	45	108	31.3	7.0
17.44	-6.12	0.35	0.93	45	107	32.8	7.2



**Figure A3.** IRIS  $100\ \mu m$  observations overlaid with regions used to extract the emission for the bow-shock (black ellipse) and backgrounds (red ellipses).

**Table A5.** Absorbed and unabsorbed fluxes ( $F_{X\text{-ray,A}}$ ,  $F_{X\text{-ray}}$ ) and luminosities ( $L_{X\text{-ray,A}}$ ,  $L_{X\text{-ray}}$ ) for different temperatures  $T$ . The values were obtained with PIMMS for the region marked (dashed rectangle) in Fig. 8 for both ROSAT PSPC (0.4–1.2 keV) and MAXI SSC (0.7–1.0 keV) X-ray observations, assuming a distance of 2.5 kpc. An average column density of  $N_{\text{H}} = 5.8 \times 10^{21} \text{cm}^{-2}$  was assumed.

$T$ (K)	MAXI SSC (0.7–1.0 keV)				ROSAT PSPC (0.4–1.2 keV)			
	$F_{X\text{-ray,A}}$ ( $\text{erg s}^{-1} \text{cm}^{-2}$ )	$L_{X\text{-ray,A}}$ ( $\text{erg s}^{-1}$ )	$F_{X\text{-ray}}$ ( $\text{erg s}^{-1} \text{cm}^{-2}$ )	$L_{X\text{-ray}}$ ( $\text{erg s}^{-1}$ )	$F_{X\text{-ray,A}}$ ( $\text{erg s}^{-1} \text{cm}^{-2}$ )	$L_{X\text{-ray,A}}$ ( $\text{erg s}^{-1}$ )	$F_{X\text{-ray}}$ ( $\text{erg s}^{-1} \text{cm}^{-2}$ )	$L_{X\text{-ray}}$ ( $\text{erg s}^{-1}$ )
$10^7$	$1.5 \times 10^{-9}$	$1.1 \times 10^{36}$	$6.1 \times 10^{-9}$	$4.6 \times 10^{36}$	$1.5 \times 10^{-9}$	$1.1 \times 10^{36}$	$5.3 \times 10^{-9}$	$3.9 \times 10^{36}$
$10^{6.5}$	$1.5 \times 10^{-9}$	$1.1 \times 10^{36}$	$6.6 \times 10^{-9}$	$5.0 \times 10^{36}$	$1.5 \times 10^{-9}$	$1.1 \times 10^{36}$	$7.1 \times 10^{-9}$	$5.3 \times 10^{36}$
$10^6$	$1.8 \times 10^{-9}$	$1.3 \times 10^{36}$	$9.5 \times 10^{-9}$	$7.1 \times 10^{36}$	$2.0 \times 10^{-9}$	$1.5 \times 10^{36}$	$4.2 \times 10^{-8}$	$3.1 \times 10^{37}$

**Table A6.** Definition of rectangular regions used for the analyses of MAXI SSC and ROSAT PSPC observations. These results were used in Subsection 3.1. The signal region is highlighted in bold, while the remaining ones are background regions. The rectangle is defined with width  $w$  in North-South and height  $h$  in East-West direction if the angle  $\theta$  is 0. Galactic longitude and latitude are  $l$  and  $b$ .

$l$	$b$	$w$	$h$	$\theta$
(deg)	(deg)	(deg)	(deg)	(deg)
<b>17.1</b>	<b>-3.5</b>	<b>3.7</b>	<b>4.5</b>	<b>2.0</b>
26.3	-10.6	3.7	4.5	0.1
21.9	-9.9	3.7	4.5	0.1

## B. Observations

### B.1 X-ray

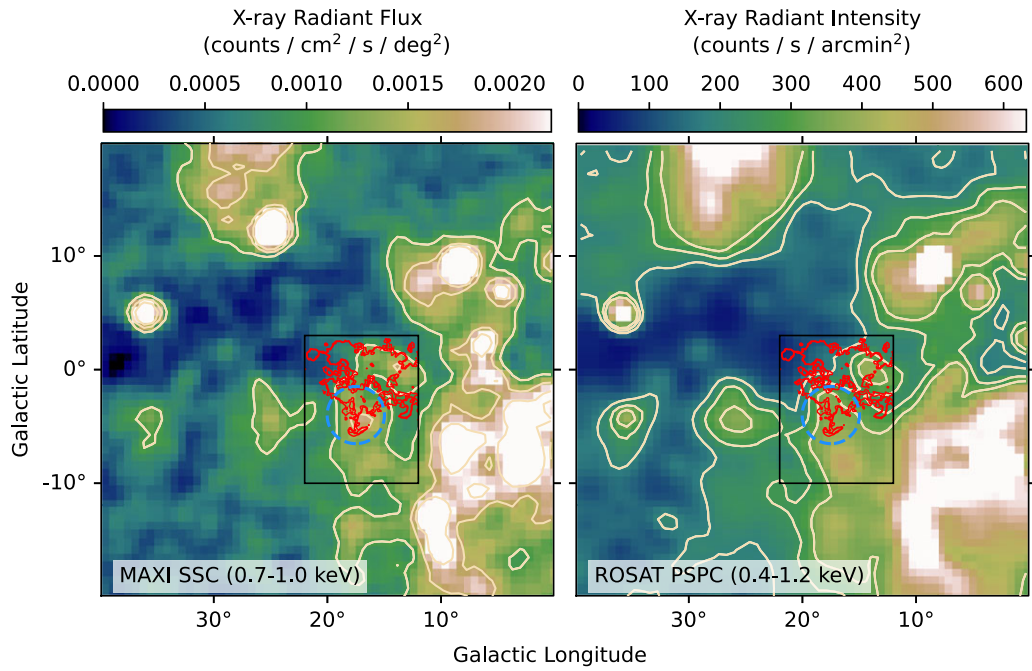
Fig. B1 present wide-field views of the MAXI SSC and ROSAT PSPC X-ray emission. The MAXI SSC image is smoothed with a Gaussian with a standard deviation of 1 pixel (10 arcmins in length). B

In Figs. B2 and B3, we compare MAXI SSC (left) and ROSAT PSPC (right) X-ray intensities (top), absorbed fluxes (middle) and unabsorbed fluxes (bottom). We used PIMMS to correct for photoelectric absorption as discussed in Subsection 3.6. The high flux regions in the figure are associated with the HII regions G018.426+1.922 and G016.993+0.873 from Anderson *et al.* (2014).

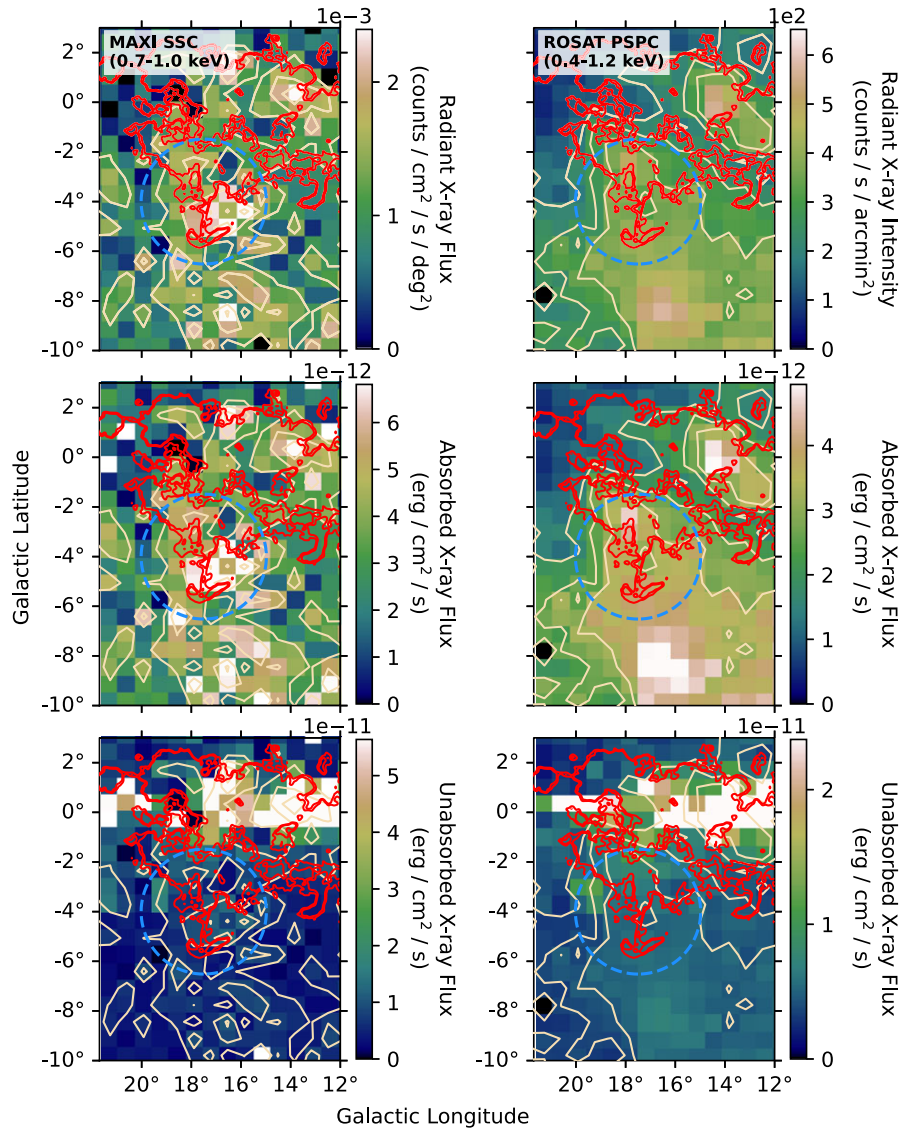
### B.2 Molecular Hydrogen

We used Dame *et al.* (2001)  $^{12}\text{CO}$  observations to understand the molecular clouds towards the Scutum Supershell. Fig. B4 shows the  $^{12}\text{CO}(1-0)$  map (converted to  $\text{H}_2$  column density), covering different velocity ranges. The CO maps only cover  $|b|5^\circ$ , so that the  $\text{H}\alpha$  bow-shock region is not encompassed. The Nanten CO emission (15–30 km/s) from Mizuno & Fukui (2004) encompasses the water maser G016.8689–02.1552 (Urquhart *et al.* 2011), and the gamma-ray source GeV-B towards the north of the Galactic worm GW 16.9–3.8 and south of the high-mass X-ray binary LS 5039 (Koo *et al.* 1992).

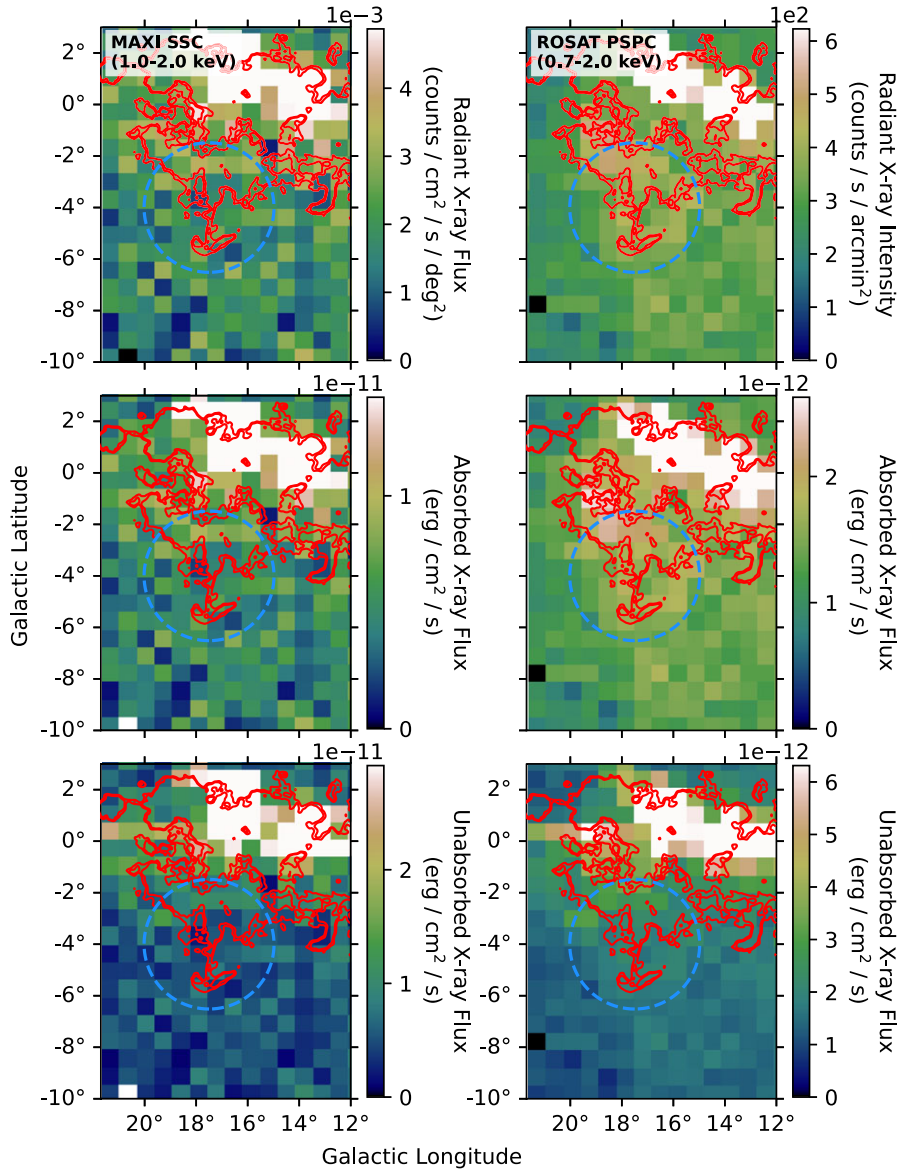




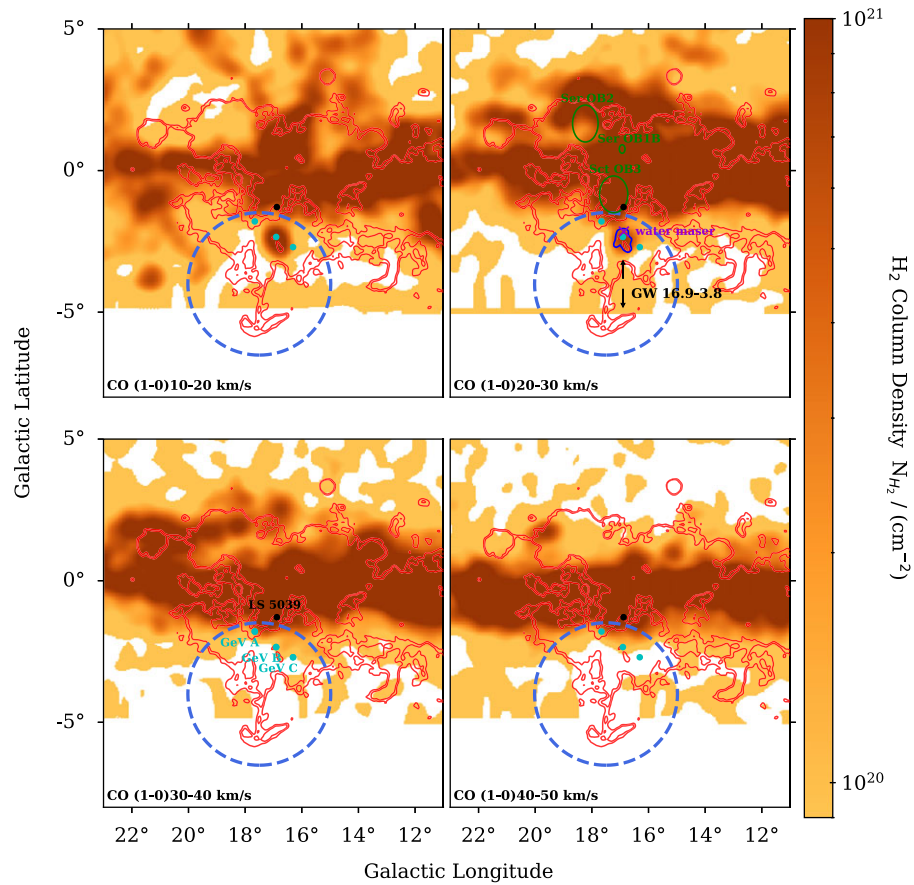
**Figure B1.** Soft X-ray maps in a wider region around the Scutum supershell (dashed blue circle). Emission from MAXI SSC (left; Nakahira et al. 2020) for energies 0.7–1.0 keV is compared with ROSAT PSPC (right; Snowden et al. 1997) for energies 0.4–1.2 keV. Brown contours represent X-ray emission at 5, 10, and 15 $\sigma$  level, and red contours H $\alpha$  emission at 40 and 50 Rayleigh (Finkbeiner 2003). The black box indicates the region shown in the other X-ray images (Figs. B2, B3).



**Figure B2.** Soft X-ray emission from MAXI SSC (left; Nakahira *et al.* 2020) and ROSAT PSPC (right; Snowden *et al.* 1997) towards the Scutum supershell (blue circle). We compare X-ray intensities (top), absorbed fluxes (middle), and unabsorbed fluxes (bottom), and used PIMMS to correct for photoelectric absorption. X-ray contours (brown) are shown at 5, 10, and 15  $\sigma$  for both MAXI SSC (0.7–1.0 keV) and ROSAT PSPC (0.4–1.2 keV). The temperature assumed in the PIMMS model for both analyses is  $T = 10^7$  K. The  $H\alpha$  contours (red) are shown at 40 and 50 Rayleigh.



**Figure B3.** Hard X-ray emission from MAXI SSC (left; Nakahira et al. 2020) and ROSAT PSPC (right; Snowden et al. 1997) towards the Scutum supershell (blue circle). We compare X-ray intensities (top), absorbed fluxes (middle), and unabsorbed fluxes (bottom), and used PIMMS to correct for photoelectric absorption. X-ray contours (brown) are shown at 5, 10, and 15  $\sigma$  for both MAXI SSC (1.0–2.0 keV) and ROSAT PSPC (0.7–2.0 keV). The temperature assumed in the PIMMS model for both analyses is  $T = 10^7$  K. The  $H\alpha$  contours (red) are shown at 40 and 50 Rayleigh.



**Figure B4.**  $\text{H}_2$  column density maps using  $^{12}\text{CO}$  ( $J=1-0$ ) emission from Dame et al. (2001), integrated over different velocity ranges.  $\text{H}\alpha$  emission at 40 and 50 Rayleigh (red) (Finkbeiner 2003) is indicated as black contours, while the Scutum Supershell boundary is shown as a blue dashed circle (Callaway et al. 2000). GeV A, GeV B, and GeV C (cyan dots) are *Fermi*-LAT GeV gamma-ray sources (Araya et al. 2019), and LS 5039 (black dot) is a high-mass X-ray binary featuring high-energy gamma-ray emission. The 20–30 km/s map includes the Nanten CO cloud (dark blue contour) for the 15–30 km/s range from Collins et al. (2021), and the water maser G016.8689–02.1552 (purple cross) (Urquhart et al. 2011). The Galactic worm GW 16.9–3.8 is indicated by black arrows (Koo et al. 1992).



## C. Catalogues

### C.1 Atomic Hydrogen Supershells

Table C1 lists the Galactic supershells so far identified with total energies above  $10^{52}$  erg to compare the Scutum supershell with other supershells.

### C.2 O and OB Stars

OB Stars from Reed (2003) were used, employing Astropy and SIMBAD to determine the spectral type and distance of each star. Table C2 lists all O-type stars in the region of interest. The distance of each star was determined using Gaia DR3 parallax Gaia Collaboration (2020). We calculate the distance  $r$  to the bow-shock, using the coordinates Galactic longitude of  $17.3^\circ$  and Galactic latitude of  $-5.5^\circ$  (Fig. 9). Similarly, Table C3 lists stars with spectral type ‘OB’ (uncertain type of O or B).

**Table C1.** List of Galactic supershells (GSH) with total energy ( $E$ ) above  $10^{52}$  erg, age, mass, and distance ( $D$ ). Data are from Suad et al. (2019), Ehlerová, Palouš, & Huchtmeier (2001) (\*), McClure-Griffiths et al. (2006) (\*), Dawson et al. (2011) (◆), and Kaltcheva et al. (2014) (▲). The Scutum Supershell is highlighted in boldface.

GSH	$\log(E)$ (erg)	Age (Myr)	Mass ( $10^4 M_\odot$ )	$D$ (kpc)
016-01+71	52.4		5.8	6.3
018-04+44	52.0		62	3.3
022+01+139	53.0		6.4	9.5
029+00+133	52.6		6.3	8.7
033+06-49	52.9		6.8	22
034-06+65	52.1		6.0	4.6
041+01+27	52.9		6.7	2.0
046-01+83	52.0		6.0	6.9
052+07+39	52.1		6.0	3.1
057+01-33	53.6		7.0	13.8
061+00+51	52.1		5.7	4.8
064-01-97	53.8		7.1	16.9
071+06-135	54.2		7.8	21.6
075-01+39	52.9		6.2	2.6
081-05-37	52.9		6.9	7.5
088+02-103	54.1		7.3	12.6
091-04-69	52.8		6.8	9
091+02-101	52.3		6.3	12.3
095+04-113	53.5		7.3	12.9
103+05-137	53.4		7.0	15.6
108-04-23	52.7		6.1	2.5
117-07-67	52.2		6.0	6.3
123+07-127	53.3		7.4	15.1
128+01-105	52.2		6.3	11.4
139-03-69	54.8		8.2	7.1
20+05+23	52.2		6.0	4.8
223-02+35	52.6		6.6	3.5
224+03+75	53.4		7.0	7.6
242-03+37	54.2		7.5	3.6
242-03+37*	53.0	21	4.8	1.6
277+00+36◆	53.0	>10	>100	6.5
287+04-17◆	52.0	>10	>100	2.6

**Table C2.** List of O-type stars from Reed (2003). Their spectral type was found using *Astropy* and SIMBAD, and the stars are limited to the region between  $15.5^\circ \leq l \leq 21^\circ$  and  $-5^\circ \leq b \leq 5^\circ$ . The stars' magnitudes (mag) are from Reed (2003) (mag). The distances to Earth (based on Gaia DR3 parallax measurements; Gaia Collaboration 2020) and the distances  $r$  to the bow-shock (GL= $17.3^\circ$  and GB= $-5.5^\circ$ ) are also listed. Galactic longitude and latitude are  $l$  and  $b$ , respectively.

Name	mag	$l$ (deg)	$b$ (deg)	Dist (pc $\pm$ 5%)	S(type)	S(type) reference	$r$ (pc)
LS IV -15 42	10.9	15.70	-0.06	2 877.7	O8.5V+O8.5V	a	629.8
LS IV -13 3	11.6	15.88	4.23	2 125.8	ON6V((f))	a	195.9
HD 168444	8.8	16.20	-0.01	1 542.7	O9.5/B0Iab	c	796.5
V* QR Ser	9.2	16.81	0.67	2 078.1	O9.5III+B3-5V/III	h	307.9
V* V479 Sct	12.0	16.88	-1.29	2 040.8	ON6V((f))z	a	319.0
BD-14 5040	10.8	16.90	-1.12	1 716.7	O5.5V(n)((f))	a	614.5
LS IV -13 14	11.0	16.91	0.85	1 830.1	O9V	g	512.6
HD 168075	8.8	16.94	0.84	1 682.0	O7V(n)((f))z	b	651.1
BD-13 4930	9.4	16.94	0.77	1 786.0	O9.7V	g	554.6
BD-13 4928	10.1	16.97	0.82	1 692.0	O9.7IVnn	g	641.8
HD 168137	9.5	16.97	0.76	1 881.1	O8Vz	a	467.9
BD-13 4929	10.4	16.98	0.82	1 703.0	O7V+B0.5V+B0.5V:	h	631.6
BD-13 4927	10.2	16.99	0.85	1 758.7	O7II(f)	b	578.7
HD 168504	10.0	17.03	0.35	1 717.3	O7.5V(n)z	a	625.1
HD 167330	9.6	17.66	2.16	1 728.0	O9.5/B0Ia/ab	c	590.3
HD 169727	9.9	17.99	-0.82	2 090.3	O7II	d	293.7
BD-12 5004	11.3	18.22	1.17	1 874.7	O9IV	d	466.5
BD-12 4979	10.4	18.25	1.69	1 912.0	O9.5V	e	423.3
LS IV -12 12	10.4	18.32	1.87	1 829.1	O6V((f))	a	498.1
HD 168112	9.8	18.44	1.62	2 006.0	O5III(f)	b	341.8
BD-12 4984	10.0	18.53	1.77	2 026.7	O9V	o	321.4
HD 168461	10.2	18.57	1.25	2 125.4	O7.5V((f))Nstr	a	259.3
HD 171589	8.3	18.64	-3.09	1 848.7	O7.5II(f)	b	466.0
BD-12 5042	11.6	18.69	-0.02	2 181.0	O9Ib	d	272.8
V* RY Sct	10.4	18.71	-0.13	2 106.1	O9.7Ibep	l	309.3
HD 168206	9.1	18.91	1.75	2 042.4	WC8+O8/9III/V	f	311.3
HD 166734	8.4	18.92	3.63	1 759.0	O7.5Iabf	b	550.6
BD-11 4586	9.4	19.08	2.14	2 009.6	O8Ib(f)	b	332.6
BD-11 4620	10.2	19.15	0.67	2 139.9	O5	o	274.8
BD-12 5039	10.8	19.17	0.32	2 115.0	O6	k	301.4
HD 171198	9.8	20.03	-1.74	2 173.9	O7:	c	235.1
BD-10 4682	9.6	20.24	1.01	1 979.8	O7Vn((f))	a	394.3
BD-11 4674	10.2	20.98	-1.22	2 887.6	O9	o	635.3
HD 175754	7.0	16.3	-9.9	2 181.9	O8II(n)((f))p	e	367.8
HD 175876	6.9	15.3	-10.6	2 463.1	O6.5III(n)(f)	e	240.9

<sup>a</sup>Maíz Apellániz *et al.* (2016).

<sup>b</sup>Sota *et al.* (2011).

<sup>c</sup>Houk & Smith-Moore (1988).

<sup>d</sup>Vijapurkar & Drilling (1993).

<sup>e</sup>Sota *et al.* (2014).

<sup>f</sup>Skiff (2014).

<sup>g</sup>Maíz Apellániz *et al.* (2022).

<sup>h</sup>Sana *et al.* (2009). Reed (2003).

<sup>o</sup>Nassau & Stephenson (1963).

<sup>l</sup>Walborn (1982).

**Table C3.** List of OB stars from Reed (2003). Their spectral type was found using *Astropy* and SIMBAD, and the stars are limited to the region between  $15.5^\circ \leq l \leq 21^\circ$  and  $-5^\circ \leq b \leq 5^\circ$ . The stars' magnitudes (mag) are from Reed (2003) (mag). The distances to Earth (based on Gaia DR3 parallax measurements; Gaia Collaboration 2020) and the distances  $r$  to the bow-shock (GL=17.3° and GB=-5.5°) are also listed. Galactic longitude and latitude are  $l$  and  $b$ , respectively.

Name	mag	$l$ (deg)	$b$ (deg)	Dist (pc)	S(type)	S(type) reference	$r$ (pc)
LS IV -12 3	11.4	16.23	4.88	1 641.49	OB-	a	765.19
BD-12 4915	11.5	16.81	4.35	1 992.82	OB	a	479.4
LS 4657	11.9	15.57	3.49	2 097.31	OB+	a	400.6
LS IV -13 4	11.6	15.60	2.93	1 682.36	OB-	b	698.3
LS IV -14 10	11.4	15.77	1.63	1 751.00	OB-	b	616.0
BD-14 4937	10.8	15.60	1.49	1 280.73	OB-	b	1 056.0
BD-12 4949	10.7	17.17	2.32	1 656.45	OB	a	707.6
TYC 5685-3491-1	11.4	17.89	1.93	1 675.32	OB	a	684.1
LS IV -13 7	11.6	16.81	1.13	1 680.39	OB-	b	669.6
BD-12 4964	10.8	18.11	1.80	2 025.93	OB	a	387.6
LS IV -14 28	11.5	15.87	0.50	1 520.45	OB	b	815.7
LS IV -12 14	11.6	18.31	1.78	1 920.49	OB	b	467.8
BD-12 4975	11.1	18.20	1.70	1 944.39	OB-	a	446.8
BD-12 4977	10.7	18.16	1.67	2 144.08	OB	b	311.3
BD-12 4978	10.4	18.24	1.70	2 089.86	OB	b	342.7
TYC 5689-418-1	10.6	17.28	1.18	2 055.49	OB+	a	352.1
BD-12 4982	10.1	18.31	1.70	2 023.88	OB	a	386.6
LS IV -12 27	11.3	18.39	1.73	2 181.50	OB	a	296.7
LS IV -14 29	11.4	16.50	0.66	1 631.85	OB-	b	709.8
LS IV -12 32	11.0	17.98	1.33	1 593.62	OB-	b	751.9
LS IV -12 33	12.1	18.48	1.59	2 166.37	OB+	a	298.9
LS IV -12 34	10.5	18.58	1.60	2 157.96	OB-	b	303.0
BD-12 4994	10.6	18.47	1.54	2 218.27	OB	a	277.7
LS IV -14 32	11.1	16.29	0.34	1 280.57	OB-	a	1 045.2
LS IV -12 36	11.1	18.01	1.25	1 533.74	OB-	b	807.5
BD-12 4996	11.5	18.00	1.24	2 562.13	OB	a	365.2
LS IV -12 38	11.3	18.09	1.25	1 702.99	OB-	b	649.0
LS IV -12 39	11.3	18.35	1.38	2 198.76	OB-	a	278.4
BD-13 4941	10.7	17.76	0.87	2 099.95	OB+	a	313.5
BD-12 5008	10.8	18.13	1.05	1 974.33	OB	a	409.0
LS IV -09 5	11.8	20.87	2.44	1 851.85	OB-	b	547.2
LS IV -14 39	11.6	16.60	-0.07	1 940.61	OB	a	417.8
TYC 5689-1271-1	11.3	16.38	-0.24	2 351.28	OB+	a	215.5
LS 4965	11.4	17.18	0.12	1 787.94	OB-	a	555.9
TYC 5689-237-1	11.0	17.20	0.07	2 237.13	OB+	a	223.8
GSC 06265-01861	11.4	15.53	-0.82	2 125.85	OB	c	265.7
TYC 6265-2079-1	11.0	15.59	-0.82	1 683.21	OB	c	648.4
LS IV -11 16	11.9	19.75	1.25	1 533.74	OB-	b	809.8
LS 4992	11.2	17.84	0.10	1 971.99	OB+	a	391.5
LS IV -10 7	11.7	20.25	1.23	1 543.92	OB-	b	801.5
LS IV -12 47	12.6	18.88	0.44	2 010.05	OB-	a	369.0
BD-14 5029	10.6	17.23	-0.44	2 036.66	OB	a	328.5
LS IV -13 43	11.0	17.75	-0.18	1 560.30	OB-	a	767.2
UCAC4 380-107183	11.4	17.25	-0.46	2 614.37	OB-	a	370.3
TYC 5702-1189-1	11.4	16.54	-0.90	2 040.81	OB+	a	318.7

**Table C3.** Continued.

Name	mag	<i>l</i> (deg)	<i>b</i> (deg)	Dist (pc)	S(type)	S(type) reference	<i>r</i> (pc)
LS IV -14 49	11.6	17.46	-0.52	2 297.79	OB	a	192.5
LS IV -14 50	11.7	16.91	-0.84	1 634.78	OB-	b	690.3
LS IV -14 51	11.8	17.49	-0.62	1 749.78	OB-	a	581.8
LS 5016	11.7	17.62	-0.57	2 554.27	OB+:	a	317.7
LS 5022	11.1	16.10	-1.49	2 158.42	OB+	a	222.0
TYC 5702-1096-1	11.4	18.05	-0.52	1 963.09	OB	a	387.7
LS IV -12 55	11.4	18.68	-0.19	2 482.00	OB:	a	274.0
UCAC4 384-101260	11.5	18.20	-0.45	2 868.61	OB	a	600.8
TYC 5698-3744-1	11.5	18.63	-0.27	2 139.03	OB+	a	258.1
BD-14 5043	10.3	17.06	-1.15	1 179.80	OB	a	1 133.4
LS IV -13 45	11.4	18.18	-0.57	2 341.92	OB-	a	194.6
LS IV -15 46	10.8	16.51	-1.48	2 675.94	OB	a	411.0
LS IV -11 19	12.1	20.12	0.38	2 034.58	OB-e	b	355.1
LS IV -15 49	11.3	16.65	-1.45	1 906.94	OB-	b	426.6
LS IV -13 46	11.6	17.70	-0.95	2 014.91	OB-	a	335.5
BD-14 5048	11.6	16.87	-1.42	2 308.40	OB-	a	164.9
LS IV -14 63	11.1	17.47	-1.20	2 302.55	OB-	a	168.9
TYC 5698-4048-1	11.4	18.98	-0.44	2 121.79	OB	a	266.0
BD-14 5054	10.1	17.10	-1.44	1 591.84	OB-	b	726.5
BD-14 5058	9.5	17.77	-1.15	1 922.33	OB-	a	414.1
LS IV -14 71	11.4	17.02	-1.62	2 039.15	OB-	b	304.4
HD 170061	9.9	17.20	-1.60	1 874.76	OB <sub>e</sub>	a	453.1
BD-13 4990	11.0	18.66	-0.91	2 053.81	OB-	a	304.7
BD-16 4894	10.4	15.65	-2.72	1 979.41	OB	a	350.2
LS IV -15 53	11.1	17.05	-2.01	1 951.98	OB-	b	376.3
LS IV -12 68	11.4	19.09	-1.23	2 331.54	OB-	a	173.9
LS IV -11 22	11.9	20.39	-0.61	1 044.38	OB-	b	1 272.5
BD-11 4652	11.5	20.27	-0.77	1 816.86	OB-	b	522.8
LS IV -12 73	12.0	19.29	-1.31	1 719.69	OB-	b	604.7
LS IV -13 59	11.7	18.89	-1.52	2 402.11	OB-	b	189.6
LS IV -13 60	12.0	19.02	-1.48	2 288.85	OB-	b	162.3
LS IV -13 61	11.5	18.46	-1.85	1 817.85	OB-	b	503.7
LS IV -13 67	11.2	18.93	-1.84	1 785.39	OB-	b	535.7
BD-12 5095	10.4	19.42	-1.73	2 146.84	OB-	a	219.6
LS IV -13 68	11.1	18.85	-2.05	2 194.42	OB-	b	176.3
LS IV -12 80	11.6	19.45	-1.80	2 602.81	OB-	b	340.2
EM* AS 309	11.2	18.54	-2.42	1 885.37	OB-e	b	433.5
LS IV -12 83	11.7	19.73	-1.81	2 338.08	OB-	a	163.1
LS IV -13 72	10.8	18.76	-2.33	2 160.76	OB-	a	191.2
BD-12 5103	11.0	20.15	-1.66	1 459.64	OB-	b	857.2
LS IV -13 74	12.0	18.99	-2.30	1 950.07	OB-	b	374.6
LS IV -14 88	11.7	18.25	-2.70	1 886.43	OB-	b	429.4
LS IV -14 89	11.9	18.28	-2.73	2 173.44	OB-	b	170.7
BD-13 5035	11.2	18.88	-2.55	2 097.75	OB-	b	237.4
LS IV -12 92	11.8	19.91	-2.07	1 301.23	OB-	b	1 010.4
LS IV -14 91	12.0	18.45	-2.83	2 151.00	OB-	b	186.1



**Table C3.** Continued.

Name	mag	<i>l</i> (deg)	<i>b</i> (deg)	Dist (pc)	S(type)	S(type) reference	<i>r</i> (pc)
LS IV -11 31	11.8	20.49	-1.88	1 479.72	OB-	b	837.3
LS IV -14 94	11.9	18.27	-3.13	2 642.70	OB-	b	357.2
LS IV -13 80	11.5	19.63	-2.80	1 924.18	OB-	b	396.9
LS IV -14 96	11.7	18.91	-3.32	1 751.92	OB-	b	556.9
LS IV -12 96	11.6	19.85	-2.87	1 076.77	OB-	b	1 229.8
LS IV -11 33	11.4	20.95	-2.46	1 751.92	OB-	b	571.2
TYC 6271-1204-1	11.8	16.41	-4.80	2 962.08	OB-	a	665.7
BD-12 5133	11.3	20.59	-3.13	2 794.85	OB-	a	513.0
BD-13 5065	10.1	19.74	-3.67	1 872.30	OB-n:	a	439.5
LS 5116	12.2	19.38	-4.13	1 787.63	OB	a	518.8
LS IV -13 86	11.7	19.94	-3.94	1 755.92	OB-	b	553.0
LS IV -14 102	11.2	19.06	-4.69	1 678.41	OB-	b	624.3

<sup>a</sup>Stephenson & Sanduleak (1971).<sup>b</sup>Nassau & Stephenson (1963).<sup>c</sup>Reed (2003).