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# A SEARCH FOR SUPERNOVA REMNANTS AT 145 MHZ WITH PAPER

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## ABSTRACT

Present astrophysical understanding of high-mass stars allows for predictions of their formation rates. High-mass stars explode in supernovae, which leave behind Supernova Remnants (SNRs) that serve as records of the stars; however the 274 observed SNRs is far below the $>1000$ predicted. This gap, hereafter known as the *SNR Defect*, could implicate the understanding of high-mass stars if confirmed. This study reports on a search for Galactic SNRs using low-frequency radio maps produced by the Precision Array for Probing the Epoch of Reionization (PAPER), a radio telescope that operates at 145 MHz. Mathematical predictions [CITE!!] of the number of observable SNRs based on known limitations showed that the SNR Defect may be made up by a complete survey. This shows that the SNR Defect is likely due to selection effects: difficulties in detecting SNRs given their location and size, and not due to a fundamental misunderstanding in star formation rates.

*Subject headings:* ISM: - molecular clouds – stars: formation – high mass – millimeter continuum

## 1. INTRODUCTION

The major classification difference between high-mass ($M > 8M_{\odot}$ ) and low-mass ($M < 8M_{\odot}$) stars is the end of their life, for which the latter explode in supernovae (SNe), which is precipitated by accumulated inert iron in the core (Arnett and Schramm 1973). The subsequent collapse of the core creates the supernova explosion, which ejects the entirety of the stars outer layers, forming a supernova remnant (SNR). The SNR consists of the expanding supernova shock wave, the ejected outer material of the star, and any dust or gas it picks up while expanding. The remnant slowly expands until its density becomes near that of the surrounding interstellar medium (ISM) making it effectively indistinguishable, and ending its existence as an SNR, which typically occurs around $10^6$ years [CITE!!]. The SNR shock releases high-velocity particles, including a barrage of electrons that produce non-thermal emissions; these relativistic electrons are accelerated and spiraled by the magnetic fields of the SNR and produce synchrotron radiation as a result making SNRs easily-detectable radio sources (e.g. Burbidge 1956; Stupar and Parker 2011).

[DOES THIS CONTRIBUTE TO THE OVERALL PAPER?] SNRs are categorized, based on their morphology, into two traditional classes:

(i) shell-like, which have a complete shell resulting from the SNR shock;

(ii) plerionic or “crab-type,” which have centrally located pulsars, also known as plerions, (Weiler and Panagia 1978)

Recent observations [CITE!!!] have extended the classification system to include:

(iii) composite, which may contain both a shell or partial shell and central pulsar; and

(iv) mixed-morphology, which contain a combination of standard SNR features and unusual characteristics including non-ejecta material and/or interactions with molecular or HI clouds (Rho and Petre 1998)

SNRs are relatively short-lived ($\sim 10^5$ yr), which means that they can serve as a record of recent star formation rates of high-mass stars, since stars of high mass has shorter lifetimes [CITE!!!]. By counting remnants, one can expect to learn about recent star formation ($< 10^6$ yr) [We could cite Brogan all over the place here... need someone else?]. Measuring the star formation rates through Fe abundance allows for a reasonable prediction of the number of galactic SNRs; however, these predictions imply that there should be far more SNRs than currently detected (e.g. Brogan et al. 2006). To date, 294 SNRs have been catalogued (Green 2014) despite the prediction based on star formation rates that $\sim 1000$ galactic SNRs exist (Li et al. 1991). Assuming a rate of two SNe per century, $\sim 2000$ SNRs are predicted in the galaxy (Pavlović et al. 2013). Additionally, Brogan et al. (2006), were able to make assumptions based on known limitations of VLA surveys in order to predict the number of SNRs that are observable at all. [What were the assumptions?] Their study yielded a result of 460 observable SNRs; this is still less than half of the observed value, which leaves many SNRs unaccounted for. This SNR Defect has thus far been attributed to selection effects, a general grouping of difficulties in observing SNRs that includes:

(i) SNRs occur in dusty regions, where the dust may absorb and/or deflect SNR emissions traveling toward earth;

(ii) since the vast majority of stars are located along the galactic plane, so are most SNRs, increasing potential source confusion (e.g. Gao et al. 2011a,b);

(iii) due to the inverse square law of observed luminosity, doubling the distance to an object reduces its apparent brightness by one-fourth (Green 1991).

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The light from SNRs located 50,000 ly away, for example, is diminished by a factor of $\sim$300;

(iv) superpositioning along the Earths line of sight, by which nearby, young and inherently dense SNRs block or severely inhibit the entire field of view behind them, making surveys of the SNR population more difficult [CITE?].

It has long been known [CITE!!!] that some larger SNRs, such as W28 and W30 [GIVE POSITIONS], have positioned within them H II regions and other sources of thermal emissions, which increase the likelihood of misidentification (Andrews et al. 1985). Brogan et al. (2006) showed that the small likelihood of actual proximity notwithstanding, the apparent proximity interferes with detection of SNRs. As a result, much has been invested in finding a method to mitigate the selection effects.

Radio surveys have typically been used to observe shell-like SNRs and are successful because of the emission spectra and morphology of those SNRs (Bandiera 2001). [NEEDS MORE EXPLANATION – this is a conference talk, we should cite a resultant publication]

Young SNRs, which are physically compact and have close-to-blackbody emission spectra are more easily detected by high-resolution surveys, whereas older SNRs, which are physically spread out and emit mostly low frequencies, are better detected with radio surveys. Stupar and Parker (2011) searched for H$\alpha$ emission coming from known SNRs in order to better visualize specific structures within the remnants with greater resolution than radio or optical. Recent X-ray surveys [CITE!!!] have also been successful in observing SNRs, but usually require supplemental information due to known limitations [for example...?] (Bandiera 2001).

While radio mitigates [messy phrasing] most of the confusion when observing the galactic plane, H II regions pose a more significant problem. H II regions, opposed to SNRs, emit thermal emissions from heating causing by a nearby high-mass stars (usually main-sequence O or B). Recent discoveries [CITE!!!] that some SNRs were actually galactic H II regions have increased the push for surveys to better differentiate them. For example, SNR G166.2+2.5 was discovered to be an H II region heated by O7.5V star BD+41 1144 (Foster et al. 2006).

This work presents the findings of a search for Supernova Remnants using the Precision Array for Probing the Epoch of Reionization (PAPER), a low-frequency radio telescope operated in South Africa ([CITE!!!, and give Long and Lat for PAPER]). Additional collected data is presented on SNR candidates from other surveys of the galactic plane at various frequencies, including the Molonglo Galactic Plane Survey (MGPS) [CITE] and the Molonglo Observatory Synthesis Telescope SNR Catalog (MOSTSNRCAT) [CITE] at 843 MHz, the Midcourse Space Experiment (MSX Egan et al. 2003, operating at 8.28–21.3 $\mu$m (36.23–14.08 THz)), as well as synthetic catalogs of SNRs at 1 GHz (Green 2014) and H II regions at 2.7 GHz (Paladini et al. 2003).

This paper discusses the effects of the study on the SNR Defect, with specific reference to the likelihood of its causality by either selection effects or a misunderstanding of star formation rates. [Give the layout of the paper in Sections]

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