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The Orion-Eridanus Superbubble - PeVatron Prospects Popped?

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ABSTRACT

The Orion-Eridanus Superbubble is the nearest superbubble to Earth. This region of overlapping and expanding supernova remnants is lit up by massive stars and filled with ionized gas. Such objects are possibly PeVatrons: celestial structures capable of accelerating cosmic rays to PeV scales. But is the Orion-Eridanus Superbubble really a PeVatron? This report elucidates the characteristics and features of the Orion-Eridanus Superbubble by presenting observations from across the electromagnetic spectrum and various modeling techniques. This analysis reveals that the Orion-Eridanus Superbubble is definitively not a PeVatron, at least not currently.

1. INTRODUCTION

Our sun is located in the Orion Arm, which is a minor spiral arm of the Milky Way. If you stargaze northeast after sunset during the winter in the northern hemisphere, you will be looking down the length of this arm where you will notice the bright and nearby stars of the constellation Orion. This region has long captivated astronomers, both professional and amateur, on account of its usefulness as a nearby laboratory for star formation research and the striking beauty of its bright nebulae. But something is lurking in our stellar backyard, a mammoth object that is too faint to see with the eye or even a small telescope. The first hints of its existence were documented by American Astronomer E. E. Barnard in 1884, who noted "...an enormous curved nebulosity encircling the belt and the great nebula, and covering a large portion of the body of the giant." (Barnard 1894). This feature is now known as "Barnard's Loop", and it is a truly massive molecular cloud that subtends about 10° in the sky. What Barnard did not know is that this arcing nebula is only a small portion of an even more gargantuan structure. It was nearly 100 years later (Reynolds & Ogden 1979) when scientists finally pieced the puzzle together and identified the $\sim 45° \times 45°$ gaseous behemoth now known as the Orion-Eridanus Superbubble.

Superbubbles are stellar nurseries and graveyards simultaneously. These are regions where high mass stars have formed and perished in supernova explosions, carving out a region of low density, hot, ionized gas (Bally 2008). Massive stars continue to form inside the bubble and along its perimeter, energizing its contents with their winds and high energy photons. This new generation of stars can also collapse in supernovae, creating smaller bubbles within the larger superbubble and energizing it further (Ochsendorf et al. 2015). The result is a complex region of molecular clouds, young massive stars, supernova remnants (SNRs), and ionized gas. As the superbubble expands into the interstellar medium (ISM), it sweeps up and compresses neutral gas on its periphery, forming a barrier between the superbubble and the ISM. Along the barrier between the ionized and neutral hydrogen, recombination of electrons with protons occurs, resulting in H α emission that defines the edge of the bubble in an observable way (Ochsendorf et al. 2015).

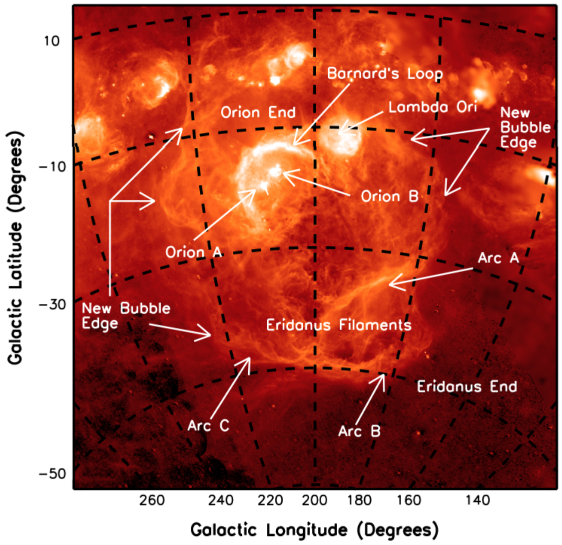
These regions of overlapping shock fronts and powerful stellar wind are promising PeVatron candidates; natural particle accelerators that can excite Cosmic Rays (CRs) to ultra-high energies. Theoretical studies have deduced that the shock fronts of young SNRs embedded in the superbubble could accelerate CR protons above 10PeV (Vieu et al. 2022). Confirmation of superbubbles acting as PeVatrons has yet to be seen, however a study of observations from the *Fermi Gamma-Ray Space Telescope*'s Large Area Telescope (LAT) have identified the Cygnus Superbubble as an accelerator of CR protons up to $\sim$300TeV. CRs that originated outside the superbubble could pass through the superbubble and be augmented by the turbulent magnetic environment therein. Some have theorized that these CRs could be prevented from penetrating deep into the superbubble, and are instead trapped and accelerated along the outskirts (Tolksdorf et al. 2019). Others have argued that superbubbles could instead confine CRs and lead to energy losses (Joubaud et al. 2020). The effect of superbubbles on CRs is poorly understood and requires more measurements to deduce.

The Orion-Eridanus Superbubble is the closest superbubble to Earth; the nearest wall of the superbubble could be as close as 134pc (Pon et al. 2016). Its proximity makes it the perfect testing ground for our theories of star formation, supernovae, interstellar gas dynamics, and CR acceleration. Could the Orion-Eridanus Superbubble be responsible for the acceleration of the CRs we detect here on Earth? I will investigate this question in this report, which will be laid out as follows: In section 2 I will provide a detailed description of the components of the Orion-Eridanus Superbubble as well as its geometry and orientation relative to Earth. In section 3 I will summarize the observations of the Orion-Eridanus Superbubble across the electromagnetic spectrum. In section 4 I will discuss the implications of the high energy electromagnetic observations for the Orion-Eridanus Superbubble's status as a PeVatron. In section 5 I will summarize my conclusions.

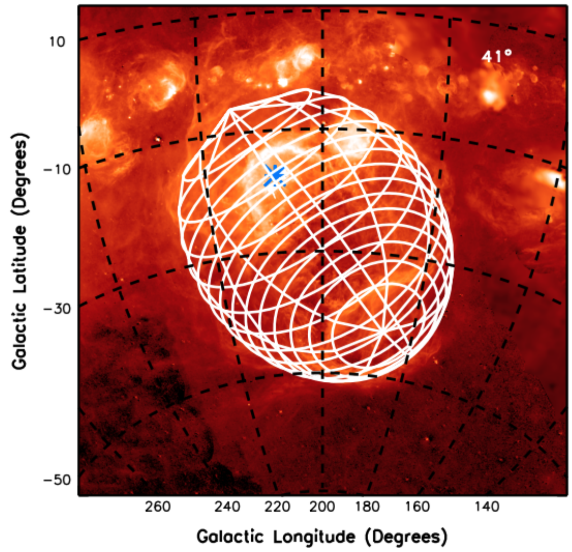
2. COMPONENTS AND MORPHOLOGY OF THE ORION-ERIDANUS SUPERBUBBLE

Perhaps the most prominent feature of the Orion-Eridanus Superbubble is Barnards loop. This curved loop of gas is luminous in Hα, and was the first feature of the

Figure 1.



(a) A Hα map of the Orion-Eridanus Superbubble created from the combined data of the Virginia Tech Spectral Line Survey (VTSS), Southern H-Alpha Sky Survey Atlas (SHASSA), and the Wisconsin Hα Mapper (WHAM), Adapted from Pon et al. (2016).



(b) A Kompaneets model fit for the Orion-Eridanus Superbubble with $\theta = 41°$, Adapted from Pon et al. (2016).

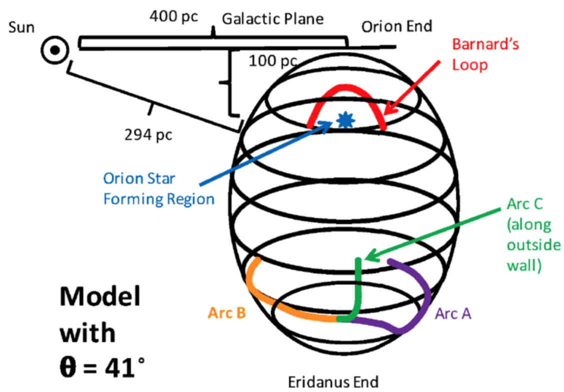
superbubble to be identified. Barnard's loop was considered to be a part of the superbubble's wall, tracing its boundary with the ISM, but this conclusion was upended when researchers discovered a dim component that was confirmed to complete a full spherical bubble with Barnard's loop. Barnard's loop is therefore a supernova remnant embedded in the Orion-Eridanus Superbubble (Ochsendorf et al. 2015). The researchers also discovered another Hα region which defines the true wall of the superbubble (Ochsendorf et al. 2015). These features are labeled in Figure 1(a).

Another brilliant feature of the Orion-Eridanus Superbubble is the λ Orionis Ring. This supernova remnant was once placed outside the superbubble's walls, but is now considered to be on the interior of the superbubble after the redefinition of the superbubble's extent (Ochsendorf et al. 2015). The eponymous bright O star λ Ori sits at the center of the shell and ionizes the region.

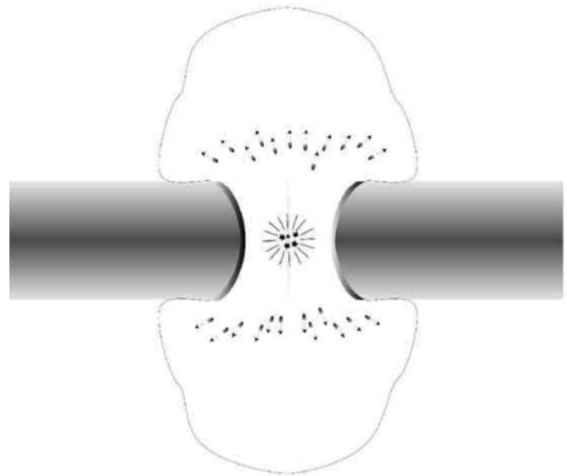
The youngest shell inside the greater superbubble surrounds the Orion Nebula Cluster. In this region, thousands of new stars are being born, including many that are quite massive (Hillenbrand & Hartmann 1998). These young stars light up the Orion Nebula, making it visible to the naked eye under dark skies. Innumerable other shells and arcs of gas are also contained within the superbubble.

The Orion-Eridanus Superbubble's general shape can be approximated with Kompaneets modeling. This is a technique where it is assumed that the superbubble's interior remains at a constant pressure while expanding into an exponential atmosphere, driven by a single stationary energy source (Pon et al. 2016). The inclination angle of the bubble is a free parameter, and one such model can be viewed in Figure

Figure 2.



(a) A schematic of the Kompaneets model fit for the Orion-Eridanus Superbubble with $\theta = 41°$, showing the orientation of the superbubble relative to the galactic plane and the Sun. Adapted from Pon et al. (2016).



(b) The galactic plane opposes the expansion of the superbubble, leading to its elongation orthogonal to the plane. As the superbubble breaches the top and bottom of the galactic plane, it can expand more freely in every direction. Adapted from Bally (2008).

1(b). With the bubble inclination constrained, its orientation relative to the solar system can be approximated as well. This is shown in figure 2(a). Kompaneets models provide a first order solution to the superbubble's geometry; its true shape is much more complex (Pon et al. 2016). It should also be noted that the true orientation of the superbubble is still a matter of debate; astronomers are split as to whether the "Eridanus End" or the "Orion End" of the superbubble are closer to the Sun (Pon et al. 2016; Joubaud et al. 2020; Bally 2008; Ochsendorf et al. 2015).

Superbubbles are not perfect spheres— far from it, in fact. After multiple supernovae hollow out the initial cavity, it expands. As it expands it encounters relatively constant and high density along the galactic plane, but lower and decreasing density in the direction orthogonal to the galactic plane. As a result, its expansion is inhibited along the plane and enhanced along the edges of the bubble that are moving away from the plane Bally (2008). A schematic of this effect is shown in Figure 2(b), where the superbubble takes on a double plumed shape. As more massive stars form and supernovae occur within the superbubble, its amorphicity is amplified because these supernovae are not necessarily at the center of the superbubble, and so act on its barriers unequally. Kompaneets model fits of the superbubble estimate that it will "blow-out" from the top of the galactic plane in 0.2-3.2Myr. When this happens, the top cap will become supersonic.

3. OBSERVATIONS OF THE ORION-ERIDANUS SUPERBUBBLE ACROSS THE ELECTROMAGNETIC SPECTRUM

3.1. *Radio Synchrotron Emission*

The lowest energy form of light detected from the superbubble is in the radio portion of the spectrum. As the superbubble expands, it compresses the material outside of its walls, freezing the magnetic field in that region. Relativistic electrons can spiral around the magnetic field lines, emitting synchrotron radiation. The light emitted from this process is inherently polarized on account of its magnetic origin, and can be distinguished from bremsstrahlung radiation by its negative spectral index (West et al. 2022). Using the Arecibo Observatory (may she rest in peace), researchers have discovered filaments of material emitting radio synchrotron light in the direction of the Orion-Eridanus Superbubble. These filaments are shown in Figure 3(a). Coincident with the synchrotron emission, these filaments have also been detected in Hα. The origin of the material strung into these filaments is still debated, but it's thought that it could be an ancient supernova remnant swept up by the expanding superbubble (West et al. 2022).

3.2. *Polarized Background Microwaves and HI 21cm Emission*

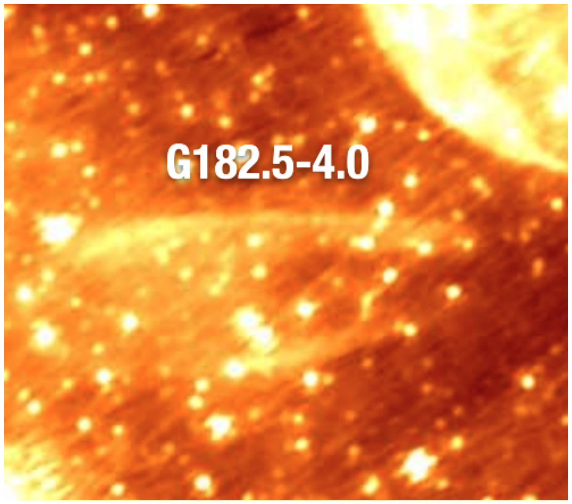
Polarized light from the Orion-Eridanus Superbubble has also been detected in the microwave regime, however the origin of this light is vastly different. Background light that passes through the superbubble must also pass through the region of compressed material and frozen magnetic fields in the superbubble's wall. This light then undergoes Faraday rotation, polarizing it in accordance with the magnetic field (Jung et al. 2024). Faraday rotation has a wavelength dependence, with higher wavelength light undergoing a stronger rotation. Researchers used the *Planck* satellite to measure the polarization of background 353-GHz microwaves to map the magnetic field in the region of the superbubble. This study showed how the superbubble has shaped the magnetic environment in the region. The researchers also derived magnetic field strengths on the order of 10s of μG for the regions surrounding the superbubble (Soler et al. 2018). The magnetic map they produced for the superbubble is shown in Figure 3(b).

There are microwave emissions that come from the Orion-Eridanus Superbubble, and these are observed at wavelength of 21cm. This corresponds to regions containing neutral atomic hydrogen (H I). If the quantum mechanical spins of the hydrogen nucleus and its sole electron are aligned, the electron can flip its spin so they are anti-aligned. The result is the emission of light with a wavelength of 21cm, which is on the lower energy end of the microwave regime. Due to this emission, the presence of H I can be mapped.

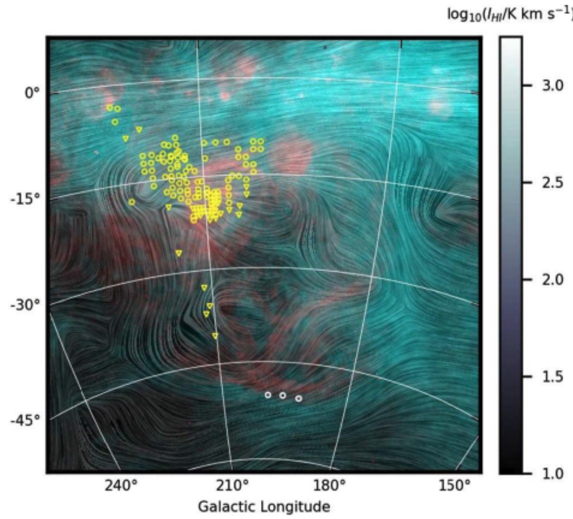
3.3. *Infrared Dust Emission*

Interstellar dust and its precursor molecules (such as CO) can be detected in the infrared portion of the spectrum. CO molecules emit in the infrared due to their rotational and vibrational modes. In the region of the Orion-Eridanus Superbubble, dust particles emit as modified black bodies with cold temperatures ($\sim$20K) (Chini et al. 1997). Maps of this dust have been produced, and are important for astrophys-

Figure 3.



(a) Filaments of hydrogen emit radio synchrotron radiation near the Orion-Eridanus Superbubble, as seen by the Arecibo Observatory. Adapted from West et al. (2022).



(b) Derived magnetic field lines are displayed here over a Hα map of the superbubble from SHASSA in red. The blue color-scale shows intensity of 21cm emisson from HI regions. Adapted from Soler et al. (2018).

ical observations in higher energy regimes, where the dust can block x-rays (Burrows 2020). Contours of 1000 μm dust emission intensity in the vicinity of the superbubble are shown in Figure 4(a). These dust filaments are not inside the superbubble, they are in-between Earth and the superbubble.

3.4. *Optical Hα Emission*

When an electron in a hydrogen atom is struck by light with sufficient energy, the electron can be excited to a higher energy state. These electron can then lose energy and transition back down to a lower energy state, emitting a photon. When the electron transitions from its 3rd excited state to its 2nd, the light emitted is in the red portion of the visible spectrum. This specific frequency of emission is called Hα, and the Orion-Eridanus Superbubble is a prolific emitter of this light. The light emitted by the massive stars in the superbubble can fully ionize hydrogen, stripping it of its electron. Along the border between the ionized and neutral hydrogen (the wall of the superbubble, and the walls of the embedded bubbles), electrons can recombine with the ionized hydrogen, placing this electron into an extremely high energy state. As the electron quickly transitions to lower energy states, Hα is emitted in abundance. A Hα map of the superbubble is presented in Figure 1(a), where the shock fronts of the superbubble and bubbles therein are clearly visible.

3.5. *Thermal X-Ray Emission*

The region inside the Orion-Eridanus Superbubble is diffuse, but extremely hot, with temperatures upwards of 1.2MK (Joubaud et al. 2020). Because the temperatures are so high, black body radiation from this region peaks in the X-Ray regime. The

ROentgen SATellite (ROSAT) measured these thermal emissions from a region of the superbubble, which are shown in Figure 4(a). Foreground dust can block these X-Rays, and so dust emission contours from the InfraRed Astronomical Satellite (IRAS) are overlaid to explain the X-Ray defecit in those regions (Burrows 2020).

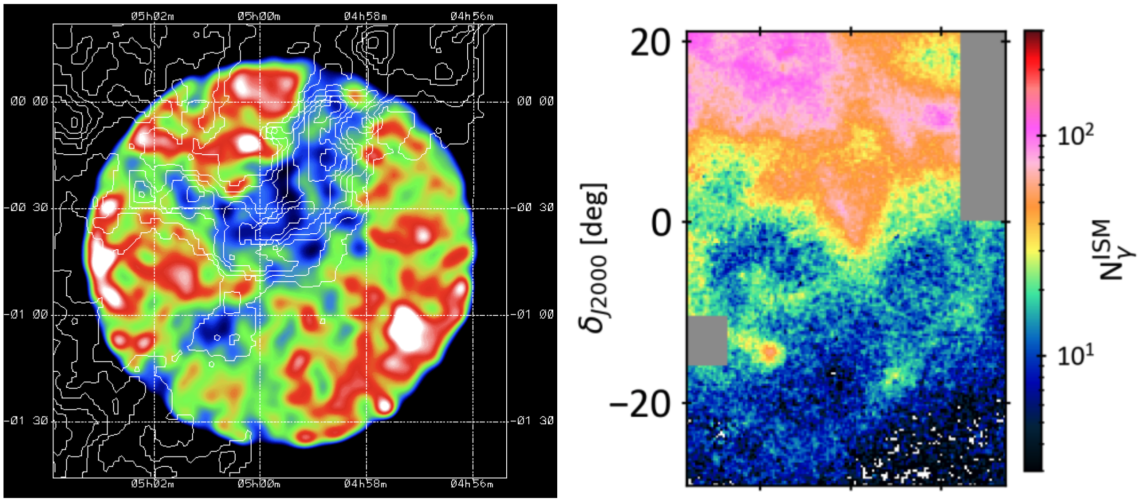
3.6. *Non-Thermal γ-Ray Emission*

CRs can be accelerated to extreme energies along the shock fronts of SNRs, perhaps like those in the Orion-Eridanus Superbubble. These CRs are charged particles, mostly protons or electrons, and so are affected by magnetic fields. Because of this, it is nearly impossible to tell where a CR detected on Earth originated from. After the CR has been accelerated at its source, it diffuses through the Milky Way and is deflected by magnetic fields along its path. As a result, when the CR reaches Earth, its incident direction no longer points to its source. However, γ-rays provide another method to identify the sources of high energy CRs. At the source, CRs that have been accelerated to high energies can collide with protons in the surrounding medium and create pions. These pions then decay and form γ-ray pairs. Because γ-rays are photons, they have no charge and are not deflected by magnetic fields. Thus, γ-rays can point back to the source of high energy CRs, and regions that are γ-ray bright are good candidates for the sources of high energy CRs. γ-rays are extremely penetrating, with diffusion lengths much larger than the dimensions of the Orion-Eridanus Superbubble (Joubaud et al. 2020). They are therefore great probes of high energy CR sources. Researchers used *Fermi* LAT to observe a region of the Orion-Eridanus Superbubble in the energy range of .25-63GeV over the course of 10 years (Joubaud et al. 2020). A plot showing the γ-ray count over a region of the superbubble can be found in Figure 4(b). The hot ionized gas in the interior of the superbubble has densities that are far too low for CRs to produce significant γ-rays, so these γ-rays originate from CRs along the superbubble walls and material external to the superbubble (Joubaud et al. 2020). The results of this study will be elaborated on in the next section.

4. A PEVATRON IN OUR BACKYARD?

On Earth, CRs have been detected with energies in excess of 10^{20}eV (Bird et al. 1995). The sources that accelerate CRs to such extreme energies have yet to be identified. But what if there was a PeVatron in the Orion Arm? With a powerful natural particle accelerator in close proximity to Earth, we would observe an over abundance of the most extreme energy CRs when compared to a more typical galactic neighborhood. In the direction of such a PeVatron, we would expect to observe more γ-rays, and the differential energy spectrum of those γ-rays would be hard (i.e. more γ-rays of higher energy compared to those originating from the solar system). Theorists have deduces that a superbubble acting as an efficient CR accelerator could exhibit a differential energy spectrum as hard as $E_{\gamma}^{-0.3}$ (Tolksdorf et al. 2019). In reality such hard sources have yet to be seen, but the Cygnus Superbubble exhibits a

Figure 4.



(a) A soft X-Ray map of a portion of the Orion-Eridanus Superbubble taken by *ROSAT*. Overlaid on this map are contours of IR emission from dust measured by *IRAS*. The regions of higher dust density block the X-Rays. Adapted from Burrows (2020).

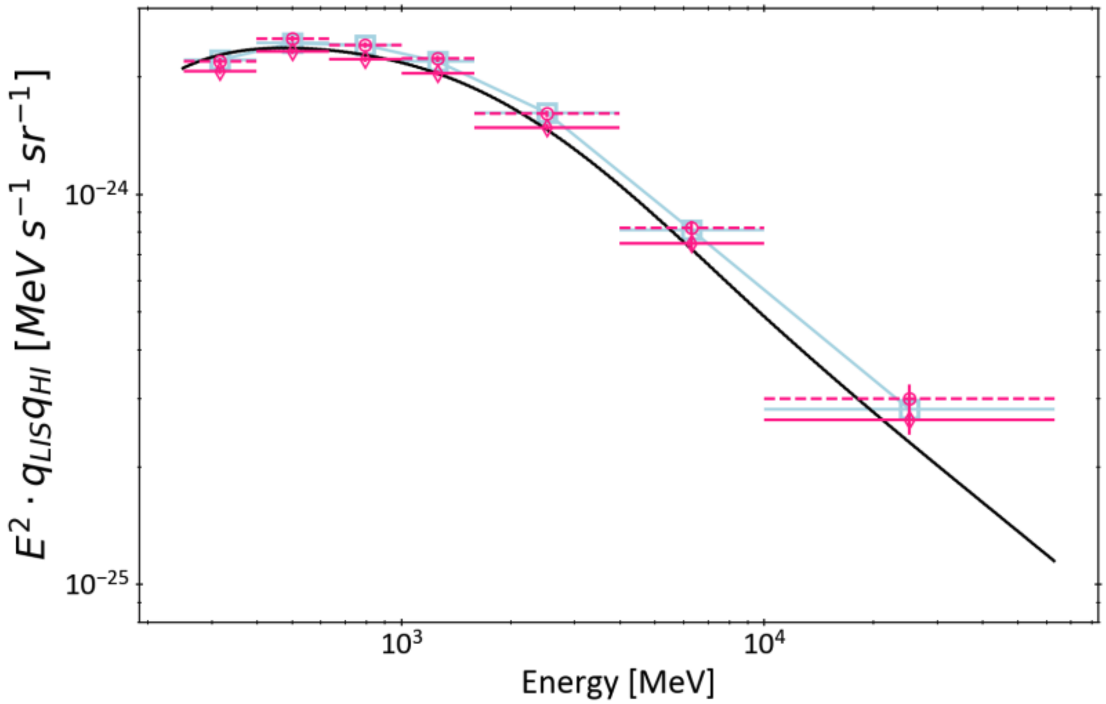
(b) A map of γ-ray counts over a region of the Orion-Eridanus Superbubble as observed by *Fermi* LAT over 10 years. These γ-rays are only those due to CR collisions at the source. Adapted from Joubaud et al. (2020).

differential γ-ray spectrum of $E_\gamma^{-2.1}$ (Ackermann et al. 2011). Within the local ISM, this spectrum takes on a softer form of $E_\gamma^{-2.7}$ (Grenier et al. 2015) above 2GeV. If the Orion Eridanus Superbubble is actively accelerating CRs to high energies, the differential γ-ray spectrum of the region would be harder, with a less negative power law index.

4.1. *Modeling γ-ray Intensity*

Measuring this index is not as simple as counting γ-rays from the superbubble and measuring their energies. This is because these γ-rays do not trace CR density, but rather the product between CR density and gas density (Grenier et al. 2015). Therefore, the γ-ray intensity will be inherently higher in the direction of regions with higher column density, even if the CR density is the same. To account for this, the researchers have modeled the material along the line of sight to the superbubble. There are four gas components that must be considered: Hα, H I, CO, and Dark Neutral Matter (DNM) (Joubaud et al. 2020). Methods of mapping these components has been discussed previously in this report, aside from DNM, which is gas that does not produce the aforementioned emissions. DNM has been shown to be mostly molecular hydrogen (Liszt & Gerin 2023), and must be accounted for to extract the differential γ-ray spectrum accurately. To determine the column density of DNM, the researchers used dust and γ-ray maps to infer the presence of material not accounted for by H I, and CO. By spatially corellating these signals they could infer the column density of DNM, which the researchers note is diffuse enough for their linear approximations to hold (Joubaud et al. 2020).

Figure 5.



The average spectral energy distribution of the γ-ray emissivity per gas nucleon ($q_S B$). The dashed lines indicate the case of optically thin H I (Joubaud et al. 2020) Blue markers show the averge emissivity of the local ISM from Casandjian (2015). The black line shows the γ-ray emissivity per gas nucleon derived from the CR spectrum of the solar system. Adapted from Joubaud et al. (2020).

After accounting for the gas column densities, the researchers also had to correct for γ-ray sources that are unrelated to CRs from the Orion-Eridanus Superbubble. These include galactic inverse Compton, isotropic extragalactic background, the Sun and Moon, isolated point sources, and instrumental residuals (Joubaud et al. 2020).

4.2. *Results*

With these factored into the model, the researchers could plot the spectral energy distribution of γ-ray emissivity from the superbubble, which is shown in Figure 5

This spectrum shows that the CR content of the Orion-Eridanus Superbubble is nearly indistinguishable from the local ISM, with a power law of about $E_\gamma^{-2.7}$ (Joubaud et al. 2020). This superbubble is not a PeVatron— It is hardly accelerating particles at all! Though the spectrum for the superbubble lays 6% above the spectrum for the solar system, systematic uncertainties in H I column density imply that these spectra are consistent with each other (Joubaud et al. 2020).

4.3. *Excuses for a Wimpy Accelerator*

There are numerous reasons that the Orion-Eridanus Superbubble is not active accelerating CRs. The first is: maybe it is. The γ-ray observations in the study were taken over the Eridanus portion of the superbubble, which is actually the older part of the bubble. It's possible that the younger Orion end of the superbubble is acting as a more efficient accelerator (Joubaud et al. 2020). Within the Eridanus end, it seems to be that the magnetic conditions inside the bubble are not conducive to particle acceleration. That is, the magnetic field is too weak, the spectrum of magnetic turbulence is too steep or a combination of both of those factors.

Comparisons to the CR accelerating Cygnus Superbubble are particularly helpful for deducing the cause of the Orion-Eridanus Superbubble's shortcoming as the two superbubbles are of similar size. However, a striking difference between them can be seen in the frequency of core collapse supernovae. The Cygnus Superbubble has produced $\sim$6 supernovae in the last million years, while the Orion-Eridanus Superbubble has produced just 1 during the same period (Joubaud et al. 2020). The injection of several fresh expanding shock fronts has likely caused the CR acceleration in the Cygnus Superbubble, while the Orion-Eridanus Superbubble has stagnated in this respect (Joubaud et al. 2020). Superbubbles may then be intermittent CR accelerators, and the Orion-Eridanus Superbubble's accelerating mechanisms will turn back on when new supernovae occur. The potential supernova progenitor population of the Cygnus Superbubble is comparable to that of the Orion-Eridanus Superbubble. Although the supernova rate should be roughly constant, it may be simple chance that the Orion-Eridanus Superbubble is in an age of relative supernova deficit from which it will eventually recover and resume accelerating CRs. Another contrast between the two superbubbles is that the Cygnus Superbubble contains the super-massive cluster Cygnus OB2, while the Orion-Eridanus Superbubble does not contain clusters of comparable mass. The tightness of the Cygnus OB2 cluster facilitates the collision of shock fronts with massive stellar winds when supernovae do occur (Joubaud et al. 2020).

5. CONCLUSION

The Orion-Eridanus Superbubble is not a PeVatron. However, it remains possible that it was in the past and that it could be again in the future. Perhaps we should be thankful that roughly 2% of the entire night sky is not occupied by a PeVatron. If that were the case, there would likely be implications for Earth's atmosphere and electronic operation. Instead of being an existential threat, the Orion-Eridanus Superbubble is a spectacle and a scientific marvel. There is still much to be learned from studying this local stellar nursery, and astronomers will continue to observe it across the entire electromagnetic spectrum to better understand galactic gas dynamics, stellar evolution, massive stars, supernovae, and more. But PeVatron hunters will have to search elsewhere, at least until the next supernova within the walls of the Orion-Eridanus Superbubble potentially reignites its particle accelerating prowess.

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