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Isolating broad-band radio technosignatures (BRaTs): a framework for detecting planetary-scale leakage

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ABSTRACT

The search for extraterrestrial intelligence (SETI) has traditionally focused on the detection of narrowband electromagnetic beacons. However, terrestrial technology is increasingly evolving towards distributed, low-power, wideband digital infrastructure. The strict adherence to narrowband filtering that characterizes most SETI surveys, therefore, risks discarding the aggregate leakage signatures of advanced civilizations by systematically misclassifying them as unstructured noise. We investigate the feasibility of detecting such planetary-scale broad-band radio technosignatures using a hierarchical observational framework. In this tiered approach, wide-field radio surveys conducted by next-generation arrays (such as the Square Kilometre Array and its precursors) perform the initial deep-field observations, with targeted Very Long Baseline Interferometry providing the definitive, high-resolution follow-up. Because broad-band continuum emission is largely insensitive to Doppler drift, long-duration 'SETI Deep Fields' are observationally viable, extending the accessible detection volume for Kardashev Type I leakage to $\sim$100 pc. To distinguish these signals from other astrophysical confounders, a multiparameter diagnostic framework is proposed. Candidate technosignatures are identified through a convergence of high brightness temperatures, negligible circular polarization, spectral non-uniformity, interstellar scintillation, and sub-milliarcsecond astrometric co-motion with nearby Galactic stars/exoplanets.

Key words: extraterrestrial intelligence – techniques: high angular resolution – techniques: interferometric – radio continuum: general.

1 INTRODUCTION

Since its inception, the search for extraterrestrial intelligence (SETI) has traditionally focused on detecting narrowband radio and optical signals (F. D. Drake 1961; R. N. Schwartz & C. H. Townes 1961; G. L. Verschuur 1973). These are characterized by their very narrow spectral occupancy, typically assumed to be only a few Hertz wide. The major advantage of searching for such signals is that they are easily distinguishable from the natural, broad-band cosmic radio background. The narrowest features associated with cosmic radio sources are Galactic masers, even these show structure only on scales >500 Hz (R. J. Cohen et al. 1987). Thus, most modern radio and optical SETI surveys continue to focus on the detection of narrowband signals, often targeting local stars (J. E. Enriquez et al. 2017; N. K. Tellis & G. W. Marcy 2017; D. C. Price et al. 2020), the galactic centre (V. Gajjar et al. 2021), and nearby galaxies (M. A. Garrett & A. P. V. Siemion 2023; C. Choza et al. 2024). The goal is specific – to detect deliberately transmitted, high-power, narrowband beacons.

Over the past 50 yr, radio leakage from our own technological civilization has changed markedly, evolving from a relatively small number of powerful narrowband transmitters, such as national radio and television broadcasts (W. T. Sullivan, S. Brown & C. Wetherill 1978), to a vast and heterogeneous population of much lower power broad-band emitters. These include cellular base stations, mobile devices, and WiFi systems (R. C. Saide, M. A. Garrett & N. Heeralall-Issur 2023), a trend that is expected to continue with the development of future communication standards such as 6G. In addition, civilian and military radar and navigation systems, satellite constellations, and other broad-band technologies now contribute to a highly complex and overlapping electromagnetic environment (P. Fan, J. Wright & T. J. Lazio 2026; R. C. Saide, M. A. Garrett & A.P.V. Siemion, in preparation). The methods for encoding information in communication signals have also evolved significantly over the last few decades. Familiar analogue modulation techniques, such as amplitude modulation (AM) and frequency modulation (FM), have given way to more complex digital modulation schemes (S. Haykin 2001).

If advanced extraterrestrial civilizations deploy broad-band communication and navigation systems of comparable or greater scale than those on Earth, their aggregate unintentional radio leakage could produce detectable emission spanning gigahertz-

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scale bandwidths. Under plausible assumptions, such broad-band signals may remain detectable across interstellar distances (R. C. Saide et al. 2023). The potential relevance of wide-band radio emission to SETI was first noted by P. F. Clancy (1980). Building on this, Messerschmitt and Morrison developed a theoretical framework for detecting extraterrestrial broad-band transmissions using matched filtering techniques (D. G. Messerschmitt & I. S. Morrison 2012; I. S. Morrison 2012). In matched filtering, receiver sensitivity increases as prior knowledge of the transmitted waveform improves. In the ideal case, the receiver knows the signal structure exactly, as occurs in terrestrial digital communication systems where the modulation and coding schemes are predefined. In SETI searches, however, the waveform of a putative extraterrestrial transmission is unknown. Either a simplified assumption must therefore be adopted, such as the monochromatic tone implicitly assumed in narrowband SETI, or the waveform must be recovered through an extensive search over possible signal structures. Given that an advanced civilization may employ numerous communication technologies, some of which may be unfamiliar to us (see M. A. Garrett 2026), the computational cost of exploring this parameter space is currently prohibitive for large-scale searches.

In recent years, observational efforts have begun to expand the SETI parameter space beyond traditional narrowband searches to include pulsed and periodic broad-band radio signals (V. Gajjar et al. 2022; A. Suresh et al. 2023). Earlier theoretical studies of broad-band radio leakage and its detectability at low frequencies (A. Loeb & M. Zaldarriaga 2007) also helped motivate technosignature surveys with the Murchison Widefield Array, including searches conducted with moderate spectral resolution ($\sim$10 kHz). More recently, B. Zuckerman (2026) discussed the detection of deliberate wideband transmissions.

The framework considered here differs from these approaches by focusing on the identification of faint, compact broad-band continuum sources through deep interferometric imaging, targeted Very Long Baseline Interferometry (VLBI) follow-up, and multiwavelength source characterization. Rather than attempting to detect individual structured transmissions, we consider the possibility that the aggregate output of many independent technological systems may produce detectable broad-band radio emission. The superposition of emissions from millions of incoherent emitters, e.g. communication links, navigation systems, radar transmissions, and other technological infrastructure distributed across a planetary surface and low-Earth orbit, would generate a spectrally extended signal that appears observationally as faint continuum radio emission, easily mistaken for unstructured noise by conventional SETI searches. Within this framework, a technologically active planet would appear not as an isolated, discrete transmission, but rather as a low-intensity, artificially generated radio continuum source, most likely spatially coincident with a star/planetary system located within our own Galaxy.

In this paper, we investigate the scientific basis for detecting broad-band radio technosignatures (hereafter BRaTs). In contrast to traditional SETI searches, we consider the regime in which the aggregate emission from many independent technological systems appears observationally as faint, broad-band radio continuum emission associated with a planetary system. A central question addressed in this work is how such emission could be distinguished from the population of faint natural radio sources that dominate the centimetre-wavelength source counts at sub-mJy and µJy flux densities. Section 2 estimates the expected broad-band radio leakage from Kardashev Type I civilizations and evaluates its detectability by radio interferometers, including the Square Kilometre Array (SKA) and global VLBI networks. We introduce the concept of SETI deep fields, and also discuss how milliarcsecond angular resolution combined with sub-milliarcsecond astrometry permits the nature and precise localization of technological aggregates to be determined. Section 3 examines the properties of BRaTs and how these can be distinguished from the principal astrophysical confounders (low-luminosity active galactic nuclei, distant star-forming galaxies, RL stars, magnetized exoplanets, pulsars, etc.). Section 4 presents a multiparameter discrimination framework based on spectral behaviour, brightness temperature, polarization properties, temporal variability, scintillation, and propagation effects. We also discuss extending our methodology to Kardashev Type II BRaTs, the effects of the ionospheric cut-off for exoplanets hosted by M-dwarf stars, and AI anomaly detection. Finally, Section 5 summarizes the main conclusions and discusses the implications of broad-band radio surveys for the future evolution of technosignature search strategies.

2 THE DETECTABILITY OF KARDASHEV TYPE I CIVILIZATIONS AS BROAD-BAND TECHNOSIGNATURES

2.1 Estimating the broad-band radio leakage from a Kardashev Type I civilization

The present-day global energy consumption of human civilization is estimated at $\sim 6 \times 10^{20}$ J yr^{-1} (Energy Institute 2024). This is equivalent to an average power of $P_{\rm tot} \sim 2 \times 10^{13}$ W, placing the Earth roughly as a Kardashev Type 0.7 civilization (C. Sagan 1973). Simulations of terrestrial radio leakage from mobile communication systems and civilian/military radars (R. C. Saide et al. 2023, in preparation) suggest that the Earth currently produces an aggregate spectral luminosity of the order $L_\nu \sim 400$ W Hz^{-1} at L band. If we assume broad-band leakage scales linearly with total power consumption, we estimate a radio leakage luminosity of $L_\nu \sim 4 \times 10^5$ W Hz^{-1}.

Consider an extraterrestrial civilization located at distance D whose technological infrastructure produces isotropic-equivalent broad-band leakage with spectral luminosity L_ν across a bandwidth $\Delta\nu$. The flux density measured here on Earth is then:

$$S = \frac{L_\nu}{4\pi D^2}. \quad (1)$$

For a source with $L_\nu \sim 4 \times 10^5$ W Hz^{-1}, located at $D = 10$ pc, the resulting aggregate flux density is approximately 33 µJy. By $D = 60$ pc, the source is $\sim$1 µJy. While these represent extremely faint emission levels, modern deep-field radio surveys are already probing the subµJy regime, and next generation arrays will surpass this (E. F. Jiménez-Andrade et al. 2024).

2.1.1 Sensitivity of VLBI to BRaTs

An artificial broad-band signal originating from an Earth-like exoplanet would appear as a spatially compact point source. In a VLBI array such a signal would be detectable across global baselines and would therefore be observed as an unresolved emitter with a high inferred brightness temperature ($T_{\rm b}$). The corresponding brightness temperature measured with a VLBI array with synthesized beam solid angle Ω is:

$$T_{\mathrm{b}} = \frac{Sc^2}{2k_{\mathrm{B}}\nu^2\Omega}. \tag{2}$$

For a Gaussian synthesized beam,

$$\Omega = 1.133\,\theta_{\mathrm{B}}^2, \tag{3}$$

where θ_{B} is the FWHM beam size. Since $\theta_{\mathrm{B}} \approx \lambda/B$ and $\lambda = c/\nu$, a lower limit on the brightness temperature of an unresolved source can be written as:

$$T_{\mathrm{b}} > \frac{SB^2}{2.266\,k_{\mathrm{B}}}. \tag{4}$$

Global VLBI arrays routinely achieve milliarcsecond resolution, and microJy sensitivities over wide fields of view (A. Njeri et al. 2023; J. F. Radcliffe et al. 2025). Using the EVN sensitivity calculator (European VLBI Network 2024), a global VLBI array observing at *C* band (∼4–8 GHz) achieves a $1-\sigma$ rms sensitivity of ∼1 μJy assuming a recording data rate of 2 Gbps and an on-source observing time of 10 h. A Kardashev Type 1 civilization, presenting leakage radiation at a level of ∼34 μJy (see Section 2.1), is therefore well detected with this set-up. Since any leakage is expected to be unresolved at a distance of 10 pc, we can only determine a lower limit on its brightness temperature, $T_{\mathrm{b}} > 1.1 \times 10^6$ K. If the emission originates from a region comparable in size to an Earth-like planet (diameter $\sim 1.2 \times 10^4$ km), the intrinsic brightness temperature would be substantially higher, of order $\sim 10^{10}$ K.

We note that the sensitivity of global VLBI arrays is expected to improve significantly in the near future with the inclusion of SKA precursors (e.g. MeerKAT) and the initial deployment of the SKA itself (C. García-Miró et al. 2019; Z. Paragi, A. Chrysostomou & C. Garcia-Miro 2019). Sensitivity estimates based on the EVN Sensitivity Calculator (European VLBI Network 2024) indicate that incorporating the SKA baseline design (SKA-AA4) will approximately double the array sensitivity, yielding a 1σ rms noise level of ∼0.5 μJy.

2.1.2 *SETI deep fields*

Traditional narrowband technosignature searches are fundamentally complicated by Doppler drift – this arises from the relative motion between the transmitter and the observer (S. Z. Sheikh et al. 2019). Since the value of the drift rate is unknown *a priori*, SETI analysis pipelines are forced to execute computationally expensive acceleration trials to mitigate signal smearing across narrow frequency channels and preserve detection sensitivity. In contrast, observations of BRaTs are largely insensitive to this effect, as by definition, they target an aggregate of emission across a wide range of frequency space. This insensitivity eliminates the need for the extremely fine spectral channelization and computationally intensive acceleration searches that characterize conventional SETI experiments. More importantly, it permits exceptionally long coherent integrations. This unique advantage enables us to introduce the concept of 'SETI Deep Fields' – prolonged observational campaigns analogous to those used to detect, for example, galaxy formation in the early universe, e.g. (R. E. Williams et al. 1996).

In principle, integration times spanning many days are already feasible using established wide-field techniques (M. A. Garrett et al. 2001; M. A. Garrett, J. M. Wrobel & R. Morganti 2005; S. Chi, P. D. Barthel & M. A. Garrett 2013; E. Middelberg et al. 2013; N. Herrera Ruiz et al. 2018; J. F. Radcliffe et al. 2019; R. P. Deane et al. 2024) combined with advanced multisource calibration (J. F. Radcliffe et al. 2016). Crucially, these calibration methods can extend coherence times indefinitely, permitting arbitrarily long on-sky integrations. If total integration times of the order of ∼1000 h are achieved through deep commensal surveys, sensitivities will improve by a factor of 10. When combined with the full capabilities of SKA AA4, such deep integrations would extend the detectable range of Kardashev Type I leakage to distances of up to 100 pc with detections being made at a signal-to-noise ratio of ∼7. We note that the ngVLA can achieve similar sensitivities. Naturally, these prolonged observational campaigns would simultaneously facilitate a wealth of ancillary high-resolution radio data.

2.1.3 *Signal localization and proper motion*

Phase-referenced VLBI observations provide astrometric precision at the sub-milliarcsecond level, enabling accurate localization of compact broad-band emitters. A good example of this has been the localization of Fast Radio Bursts using VLBI techniques (B. Marcote et al. 2020). At a distance of 100 pc, an angular scale of 1 mas corresponds to a linear distance of approximately 0.1 au. Such precision allows candidate technosignatures to be associated directly with specific components of planetary systems.

For nearby stellar systems (10–100 pc), sub-milliarcsecond astrometry corresponds to linear scales of ∼0.001–0.01 au. This resolution is sufficient to distinguish emission originating from the stellar surface (e.g. stellar flares) from emission associated with a planetary orbit. Such localization therefore provides an important diagnostic for identifying planetary-scale technological emitters.

VLBI astrometry can also detect orbital motion in compact radio sources via multi-epoch observations made on time-scales of months to years (M. A. Garrett 2018). For example, a planet with an orbital radius of 0.01 au at a distance of 100 pc subtends an angular displacement of ∼0.1 mas. Tracking such motion offers an additional method for confirming the association of a radio source with an exoplanetary system. We note that similar techniques may also allow the detection and tracking of artificial spacecraft emitting powerful radio signals, with observable motion occurring on time-scales ranging from years for slow-moving objects to days for relativistic trajectories.

2.1.4 *Cross-matching with astronomical catalogues*

The precise localization afforded by VLBI enables robust cross-identification with existing astronomical catalogues. It will be important that any SETI Deep Field projects target areas of the sky with excellent auxiliary multiwaveband coverage. Candidate broad-band emitters can be compared with stellar catalogues such as *Gaia* (Gaia Collaboration 2023) to determine whether their milliarcsecond-accurate positions coincide with known stars or offset planetary systems. We will return to this discussion in the next section.

3 DISCRETE ASTROPHYSICAL CONFOUNDERS

The identification of BRaTs in the 1–10 GHz regime requires discrimination against natural compact radio emitters. Although several astrophysical processes can generate high brightness temperatures and broad-band emission that masquerades as unstructured noise, they differ systematically from a planetary-scale technological source in their spectral behaviour, polarization properties, propagation signatures, and temporal variability. Often, no single observable is decisive; rather, a consistent set of diagnostics must be considered when evaluating candidate signals.

In this section, we evaluate the principal astrophysical confounders present in deep radio surveys and establish the key discriminating features required to distinguish them from genuine technosignatures. We first of all list the likely properties of BRaTs.

3.1 Properties of BRaTs

We expect genuine BRaTs to exhibit the following defining characteristics:

(i) High brightness temperature and compact morphology: As outlined in Section 2, planetary-scale BRaTs will be observed by global VLBI networks as faint, unresolved point sources, yielding inferred brightness temperatures of $T_{\rm b} \gtrsim 10^6$ K.

(ii) Galactic kinematics: A local technosignature (10–100 pc) will probably be gravitationally bound to a nearby stellar system. Consequently, it will exhibit significant proper motion and annual parallax ($\gtrsim$10 mas yr^{-1}), alongside potential orbital kinematics.

(iii) Spectral shape: Because technological aggregates are shaped by engineering constraints rather than astrophysics, their broad-band emission is expected to display distinct spectral non-uniformity. This includes 'notches' corresponding to planetary atmospheric absorption, sharp cut-offs dictated by regulated frequency allocations, or localized regions of enhanced power resulting from specific high-energy applications (e.g. microwave power transmission).

(iv) Polarization: Negligible circular or linear polarization, reflecting the incoherent aggregation of millions of independent, randomly oriented transmitters.

(v) Interstellar scintillation (ISS) and temporal modulation: A planetary-scale emitter at a distance of 10 pc subtends an angular size of only ∼8 μas, acting as an extreme point source. This will subject the signal to strong, broad-band ISS (B. J. Rickett 1990), producing stochastic amplitude variability as predicted by J. M. Cordes, J. W. Lazio & C. Sagan (1997) and B. Brzycki et al. (2023). Crucially, these short-term propagation effects will likely be superimposed upon a highly stable, long-term diurnal modulation associated with a rotating host planet.

(vi) Host system identification: Through precise VLBI astrometry, candidate BRaTs can be unambiguously cross-matched with nearby Galactic stars using optical and infrared catalogues – most notably *Gaia* (Gaia Collaboration 2023). This precise localization will confirm their origin within the local Milky Way. Small offsets from *Gaia* stellar positions are expected.

3.2 Extragalactic radio sources

The dominant confounding sources to be found in deep centimetre-wave radio surveys is extragalactic in origin, primarily comprising Star-forming Galaxies (SFGs) and Active Galactic Nuclei (AGN). We consider here how their characteristics compare to BRaTs.

3.2.1 *Star-forming galaxies (SFGs)*

SFGs dominate the faint radio source population at flux densities $S_\nu \lesssim 100\,\mu$Jy (M. Giulietti et al. 2025). Their radio emission is primarily due to non-thermal synchrotron radiation from cosmic-ray electrons accelerated in supernova remnants. Despite their abundance in deep radio surveys, SFGs can be readily distinguished from BRaTs through several key observational properties:

(i) Brightness temperature: SFGs are generally resolved by VLBI observations and exhibit relatively low brightness temperatures, typically $T_{\rm b} \lesssim 10^5$–10^6 K (J. J. Condon 1992).

(ii) Infrared–radio correlation: SFGs follow the well-established infrared–radio correlation in both the local (P. C. der Kruit 1973; G. Helou & M. D. Bicay 1993) and high-redshift universe (M. A. Garrett 2002; P. N. Appleton et al. 2004; E. J. Murphy 2009; R. J. Ivison et al. 2010), and exhibit extended optical morphologies consistent with star-forming galaxies.

(iii) Radio morphology: SFGs typically have angular sizes of ∼0.5–2 arcsec, with radio emission tracing the optical disc of the host galaxy (T. W. B. Muxlow et al. 2005).

(iv) Cosmological distances: Multiwavelength cross-matching with wide-area surveys (e.g. Dark Energy Survey Collaboration 2016; R. M. Cutri et al. 2021) will associate many candidate BRaTs with extended galaxies exhibiting natural spectral energy distributions (SEDs). Subsequent photometric and spectroscopic redshift measurements will confirm that these sources reside at extragalactic distances, consistent with the background population of faint radio galaxies.

3.2.2 *Active Galactic Nuclei (AGN)*

While SFGs are more numerous, AGN also represent a significant confounder and are well known for their small angular sizes (G. K. Miley 1971). Below 100 μJy, Radio-Quiet AGN begin to outnumber Radio-Loud (RL) systems (C. Mancuso et al. 2017). These sources often host weak, compact active nuclei with $T_{\rm b} > 10^6$ K, and they can remain unresolved even on global VLBI baselines. Despite this, AGN can be disqualified as technosignatures through several key filters:

(i) Astrometric kinematics: AGN are located at cosmological distances and are effectively stationary on the sky, exhibiting no measurable parallax or proper motion (H. C. Harris et al. 2016).

(ii) Spectral behaviour: AGN typically exhibit smooth, power-law spectra ($S_\nu \propto \nu^\alpha$) governed by synchrotron emission processes (J. D. Kraus 1973). This behaviour contrasts strongly with the expected spectral complexity of BRaTs.

(iii) ISS: A subset of extremely compact AGN cores exhibit ISS (J. Dennett-Thorpe & A. G. de Bruyn 2002). However, for the majority of sources, intrinsic source sizes ($\gtrsim$10^{15} cm) suppress or 'quench' scintillation-induced variability.

(iv) Cosmological distances: As with SFGs, AGN will also be identified with distant host galaxies using wide-area multiwavelength surveys. Despite their compact radio morphology, optical and infrared data will exhibit the characteristic SEDs of accreting supermassive black holes and permit redshift determinations that securely place these sources at extragalactic distances.

3.3 Exoplanetary and stellar radio emission

While extragalactic sources are by far the most numerous confounders, local Galactic sources – specifically magnetized exoplanets and active stars present a different challenge. These sources can exhibit high brightness temperatures and are astrometrically 'local,' sharing the proper motion of the target system. However, they are physically constrained by plasma physics and magnetic field strengths in ways that technological leakage is not.

3.3.1 Magnetized exoplanets

Exoplanetary radio emission is generated via the electron–cyclotron maser instability (CMI), the mechanism responsible for the auroral radio emission of Solar system planets (P. Zarka 1998, 2007). However, these natural emissions possess distinct physical characteristics that allow them to be definitively distinguished from BRaTs.

(i) Frequency cut-offs: CMI emission is strictly bounded by the local electron cyclotron frequency, $\nu_{\rm ce}[{\rm MHz}] \approx 2.8\,B[{\rm G}]$ (G. A. Dulk 1985). For this natural emission to contaminate the 1–10 GHz window, an exoplanet would require extreme magnetic field strengths of $B \gtrsim 350$–3500 G. Such values are orders of magnitude higher than Jupiter's polar field ($\sim$14 G) and far exceed theoretical estimates of the maximum plausible exoplanetary field limit of $\sim$100 G (Y. Hori 2021).

(ii) Temporal and spectral behaviour: Planetary CMI is fundamentally sporadic, characterized by transient bursts with rapidly drifting dynamic spectra (e.g. Jovian decametric arcs) (E. Mauduit et al. 2023). This erratic natural emission is entirely distinct from the persistent and stable broad-band behaviour defining candidate BRaTs.

(iii) Polarization: CMI emission is intrinsically highly circularly polarized (often approaching 100 per cent) in contrast to the aggregate leakage of BRaTS which we expect to be unpolarized.

3.3.2 Active stars and M-dwarfs

Late-type stars, particularly M-dwarfs and flare stars, are prolific radio emitters across the GHz regime, producing both incoherent gyrosynchrotron radiation and coherent bursts (T. S. Bastian et al. 1990; J. Villadsen & G. Hallinan 2019). They can be distinguished from technosignatures through the following:

(i) Astrometric offset: At distances of 10–100 pc, a planet in an au-scale orbit exhibits an angular offset of $\sim$10–100 mas from its host star. VLBI's sub-milliarcsecond precision can easily distinguish between emission originating from the stellar corona and emission associated with a planetary companion.

(ii) Spectral shape: Stellar gyrosynchrotron emission typically displays a smooth, peaked spectrum (transitioning from optically thick to thin).

(iii) Variability: Stellar radio activity is largely stochastic and characterized by high-amplitude flares.

3.3.3 Ultracool dwarfs (brown dwarfs)

Ultracool dwarfs (UCDs), comprising late M, L, and T spectral types, bridge the physical gap between low-mass stars and massive exoplanets. Unlike Solar system planets, UCDs frequently possess surface magnetic fields of several kilogauss (M. McLean, E. Berger & A. Reiners 2012). Consequently, they are potent sources of CMI emission that routinely extends well into the 4–10 GHz regime, directly overlapping with the optimal terrestrial microwave window for SETI.

They can be distinguished from technological leakage through the following observables:

(i) Polarization: The CMI emission from UCDs is intrinsically highly circularly polarized, frequently approaching 100 per cent (E. Berger et al. 2001), which starkly contrasts with the incoherent, unpolarized nature of aggregate technological leakage.

(ii) Temporal behaviour: UCD radio emission is characterized by strict rotational modulation, typically manifesting as highly beamed, periodic pulses on time-scales of a few hours (G. Hallinan et al. 2015). UCDs also exhibit the rapid, frequency-dependent sweeping characteristic of dynamic plasma processes.

(iii) Infrared SED: Because UCDs have extremely low effective temperatures ($T_{\rm eff} \lesssim 2500$ K), their thermal emission peaks firmly in the near- and mid-infrared (J. D. Kirkpatrick 2005). Cross-matching a candidate BRaT with infrared catalogues (e.g. 2MASS or WISE) will readily identify a UCD as a bright, exceptionally red point source with an SED deeply sculpted by molecular absorption bands (such as water and methane) (A. Burrows et al. 2001).

(iv) Natural emission: Since UCDs provide an astrophysical explanation for compact gigahertz radio emission, associating a BRaT candidate with a UCD would effectively disqualify it as an unambiguous technosignature. The exception to this is if the emission exhibits a clear, measurable astrometric offset from the dwarf star, indicating a distinct planetary origin.

3.3.4 Protoplanetary discs

Protoplanetary discs form as a consequence of angular momentum conservation during the star formation process and provide natal material for planetary systems (F. H. Shu, F. C. Adams & S. Lizano 1987). Their faint observational signatures at centimetre wavelengths are different from the expected signals of an advanced technological civilization. They can be excluded as broad-band SETI confounders based on the following physical and observational characteristics:

(i) VLBI morphology: Protoplanetary discs are physically extended objects, with radii reaching up to several hundred astronomical units (au). Simulated deep radio observations of a typical disc at 125 pc indicate that even after 1000 h of integration, the peak intensity at 11 GHz is only $\sim$4 μJy beam^{-1}, corresponding to a brightness temperature of just $T_{\rm b} \approx 30$ K (M. Hoare et al. 2015). Because they are diffuse on milliarcsecond scales, global VLBI arrays will be heavily resolved, distinguishing them clearly from the point-like BRaT.

(ii) Spectral shape: The radio continuum of a protoplanetary disc in the 1–15 GHz range is intrinsically very faint, originating primarily from the thermal emission of large (centimetre-sized) dust grains and ionized stellar winds (L. Testi et al. 2015). It lacks the engineered spectral non-uniformity we expect from BRaTs.

3.3.5 X-ray binaries (XRBs) and microquasars

Galactic X-ray binaries, comprising a compact object (a black hole or neutron star) accreting matter from a stellar companion, frequently launch powerful relativistic radio jets. In their characteristic 'hard' accretion state, these steady, compact jets produce flat or slightly inverted radio continuum spectra ($S_\nu \propto \nu^{\sim 0}$) across the centimetre regime (R. Fender 2006). Because they are local Galactic sources, they exhibit proper motion, and their unresolved cores yield high brightness temperatures.

They can be robustly differentiated from technosignatures through the following diagnostics:

(i) High-energy counterparts: As their name implies, the accretion processes in XRBs produce extremely luminous X-ray emission (R. A. Remillard & J. E. McClintock 2006). A cross-match with X-ray catalogues (e.g. from *Chandra* or *XMM–Newton*) will readily reveal the high-energy signature of an accretion disc, which is entirely absent from a planetary technosignature model.

(ii) VLBI morphology: While the core of an XRB is highly compact, deep VLBI observations frequently resolve the extended, bipolar structure of the relativistic jets (A. M. Stirling et al. 2001), breaking the point-source degeneracy. The radio source is many orders of magnitude more luminous that a Kardashev Type I BRaT.

(iii) Spectral shape: The flat radio spectrum of an XRB jet is a natural consequence of partially self-absorbed synchrotron emission along a conical geometry. It lacks the engineered spectral non-uniformity expected from BRaTs.

3.3.6 *Pulsars and neutron stars*

Historically, the highly periodic signals of radio pulsars provided the first major astrophysical confounders for SETI, initially designated as 'Little Green Men' (LGM-1) (A. Hewish et al. 1968). In recent years, they have been detected in deep radio continuum surveys as relatively faint sources (D. A. Frail et al. 2016), and are therefore a potential confounding source. Despite their extreme compactness, several discriminants separate them from BRaTs:

(i) Spectral shape: Pulsar emission is driven by coherent processes in the neutron star magnetosphere, universally producing very steep power-law spectra (typically $S_\nu \propto \nu^{-1.8}$) (S. D. Bates, D. R. Lorimer & J. P. W. Verbiest 2013). Consequently, they are overwhelmingly bright at low frequencies ($\sim$100 MHz) but rapidly fade into the GHz regime, lacking the complex spectral non-uniformity expected of a BRaT.

(ii) Temporal behaviour: Pulsars exhibit microsecond to millisecond pulse widths with extremely rigid periodicities ranging from milliseconds to seconds (R. N. Manchester et al. 2005). This rapid, clock-like pulsation is fundamentally different from the slow, phase-stable diurnal modulation ($\sim$ hours to days) expected from a rotating planetary biosphere.

(iii) Propagation effects: As true point sources, pulsars undergo strong diffractive and refractive ISS, producing characteristic intensity modulations across time and frequency (B. J. Rickett 1990). While a highly compact technosignature will also undergo ISS, the inherently pulsed emission of a neutron star allows these propagation effects to be uniquely isolated and quantified. Specifically, pulsars exhibit measurable dispersion measures, Faraday rotation, and temporal scattering tails that scale predictably with distance through the interstellar medium (D. R. Lorimer & M. Kramer 2012). BRaTs, presenting continuous or slowly varying broad-band continuum, would not yield these measurable time-of-arrival delays across frequency bands.

3.4 Terrestrial radio frequency interference

Finally, a ubiquitous confounder in any radio SETI programme is terrestrial radio frequency interference (RFI) generated by local telecommunications, radar, and satellite infrastructure. Interferometric arrays inherently suppress terrestrial RFI through fringe-rate modulation and delay-rate filtering (H. Rampadarath et al. 2012; M. A. Garrett 2018; K. Wandia et al. 2023). Signals originating from the Earth's surface or low-Earth orbit lack the sidereal motion of celestial sources; consequently, they fail to maintain phase coherence across long baselines and rapidly decorrelate during integration. As a result, RFI that has not been removed by standard flagging processes typically contributes to the general noise floor across the synthesized field of view, rather than creating discrete artefacts in the image plane. Consequently, although RFI can elevate the noise floor and reduce survey sensitivity, it is unlikely to reproduce the compact morphology, phase stability, and persistency expected of genuine BRaT candidates.

4 DISCUSSION

While the traditional SETI focus on ultra-narrowband signals remains a highly practical strategy for detecting deliberate extraterrestrial beacons, it relies on the assumption that advanced civilizations actively desire to broadcast their presence. If, instead, extraterrestrial societies are largely passive, minding their own business, searching for aggregate broad-band leakage becomes essential.

Detecting BRaTs requires a conceptual maturation of SETI, shifting the paradigm from the search for deliberate, highly conspicuous narrowband beacons to the identification of structured, planetary-scale noise. As outlined in Section 3, while natural astrophysical sources can generate faint, compact radio emission, they exhibit systematic and measurable differences from the expected properties of BRaTs. Distinguishing between these natural sources and BRaTs requires a nuanced approach, integrating diverse multiwavelength observations across the electromagnetic spectrum. In this section, we propose a comprehensive diagnostic framework in which this discrimination effort is cast.

4.1 A multiparameter diagnostic framework

No single observational metric is sufficient to decisively identify a broad-band technosignature. Robust identification instead relies on the convergence of multiple independent diagnostics across a high-dimensional parameter space, breaking the physical degeneracies of individual observables. We summarize this discrimination framework in Table 1.

4.2 Extending the framework: Kardashev Type II civilizations

A Kardashev Type II civilization (N. S. Kardashev 1964) harnesses a substantial fraction of the total energy output of its host star ($P_{\rm tot} \sim 10^{26}$ W). Direct extrapolation of broad-band radio leakage using the linear scaling adopted in Section 2.1 is unlikely to be physically meaningful on this scale. Even if only a minute fraction of the available power were emitted or lost in the form of centimetre-wavelength radiation, the resulting emission would manifest as a bright and persistent broad-band radio continuum source.

Table 1. Diagnostic matrix for distinguishing BRaTs from discrete astrophysical confounders in the 1–10 GHz regime.

Source type	Morphology (VLBI)	T_b limit	Spectral shape	Polarization	Temporal behaviour	Astrometry and kinematics
BRaTs (Type I)	Unresolved (∼μas)	$>10^6$ K	Complex, non-uniform, atmospheric notches	Negligible/weak	Phase-stable diurnal modulation + local ISS	Local (<100 pc), co-moving, astrometric offset from star
AGN	Unresolved/Core-jet	$>10^6$ K	Smooth power-law	Variable	Stochastic flares + Galactic ISS (IDV)	Cosmological, stationary background
SFGs	Extended (∼arcsec)	$<10^6$ K	Smooth power-law	Weak/unpolarized	Steady	Cosmological, stationary background
Magnetized exoplanets	Unresolved	High	Sharp high-frequency cut-off ($\lesssim$ MHz)	Highly circular	Bursty, rotationally modulated	Local, co-moving, astrometric offset from star
Active stars (e.g. M-dwarfs)	Unresolved	High	Peaked/smooth (incoherent)	Strong circular (coherent bursts)	Stochastic flaring	Local, co-moving, spatially coincident with star
UCDs (brown dwarfs)	Unresolved	High	Sharp high-frequency cut-off (∼ GHz)	100 per cent circular	Beamed, rotationally modulated pulses	Local, co-moving, coincident with IR source
XRBs and microquasars	Compact core/Resolved jets	High	Flat/inverted	Linear/variable	Steady (hard state)/Stochastic flares	Galactic (kpc scales), negligible proper motion at μJy levels, bright X-rays
Pulsars and neutron stars	Unresolved	$>10^{10}$ K	Steep power-law	Strong linear/circular	Millisecond-second periodic pulses	Galactic, high independent proper motion, highly dispersed
Protoplanetary discs	Extended (∼100 au)	∼30 K	Thermal dust/free-free emission	Unpolarized	Steady	Local, co-moving (young stellar systems)

A fundamental distinction of a Type II BRaT lies in the spatial scale of its emitting region. For example, a Type II civilization in the form of a distributed energy-harvesting network such as a Dyson swarm (F. J. Dyson 1960) would span dimensions of the order of ∼1 au. At distances of 10–100 pc, this corresponds to angular sizes of ∼10–100 mas. Consequently, the technosignature would be partially or fully resolved by global VLBI arrays at centimetre wavelengths.

While a spatially resolved Type II BRaT might initially mimic the extended radio continuum emission of a star-forming galaxy, it can be definitively isolated using our multidimensional framework. Indeed, the systematic application of this framework to deep radio survey data can place stringent constraints on or entirely rule out the presence of Type II BRaTs within the local Milky Way. Furthermore, we note that complementary optical photometry of such systems would likely reveal highly anomalous light curves, reflecting the transit signatures and engineered geometry of orbiting megastructures.

4.3 The ionospheric barrier

An important physical factor governing the detectability of planetary-scale radio emission is the ionospheric cut-off. The propagation of electromagnetic waves through a planetary atmosphere is fundamentally constrained by the local plasma frequency, ν_p. A radio signal originating from the planetary surface or low-altitude orbit can only escape into the interstellar medium if its frequency strictly exceeds this critical threshold ($\nu > \nu_p$). The plasma frequency is determined by the maximum electron number density, n_e, within the ionosphere (G. B. Rybicki & A. P. Lightman 1986):

$$\nu_p = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{m_e \epsilon_0}} \approx 8.98\sqrt{n_e}\ \mathrm{Hz}, \quad (5)$$

where e is the elementary charge, m_e is the electron mass, ϵ_0 is the vacuum permittivity, and n_e is expressed in m^{-3}.

On Earth, the dayside ionosphere typically reaches peak electron densities of $n_e \sim 10^{12}\,\mathrm{m}^{-3}$ (M. C. Kelly 2009), resulting in a characteristic radio escape cut-off of $\nu_p \approx 10$ MHz. However, ionospheric electron densities are driven primarily by photoionization from the incident extreme-ultraviolet (EUV) and X-ray flux of the host star. Exoplanets within the habitable zones of active M-dwarfs experience severe and sustained EUV fluxes (K. France et al. 2016; S. Peacock et al. 2019). Extrapolating from atmospheric models of highly irradiated exoplanets (e.g. hot Jupiters), it is plausible that peak electron densities can exceed those observed on Earth by several orders of magnitude e.g. $n_e \gtrsim 10^{14}\,\mathrm{m}^{-3}$ (T. T. Koskinen et al. 2014). Although further characterization of terrestrial exoplanet ionospheres is required, such high electron densities would undoubtedly push the local radio blackout limit into the hundreds of MHz. Under these conditions, low-frequency technological leakage would be entirely trapped beneath the plasma shield via internal reflection. Searching for BRaTs at $\gtrsim$1 GHz mitigates this risk.

We note that the presence of a sharp, low-frequency ionospheric cut-off within a broad-band spectrum could itself act as a powerful diagnostic tool. If this spectral cut-off exhibits phase-stable diurnal variation, driven by the rotating planet's varying exposure to stellar photoionization, it would strongly support the artificial, planetary-surface origin of the radio emission.

4.4 AI-driven anomaly detection

As described in Section 4.1, robust identification of broad-band technosignatures requires simultaneous evaluation of the multidimensional diagnostics detailed in Table 1. Applying this complex analysis to the hundreds of millions of compact radio sources anticipated from next-generation wide-field surveys necessitates the deployment of Artificial Intelligence (AI) and machine learning (ML) pipelines specifically tailored for high-dimensional anomaly detection. By ingesting vast, multiwavelength catalogues that incorporate astrometry, polarization fractions, spectral topology, and temporal variability metrics, unsupervised algorithms can construct a highly accurate statistical representation of the natural astrophysical background, enabling them to separate structured artificial anomalies from standard unstructured noise. This will enable the identification of isolated outliers using the appropriate combination of physical and geometric properties expected of the planetary-scale technological aggregate we envisage for BRaTs. Implementing this will be challenging, as automated pipelines must be designed to handle the inherent heterogeneity of astronomical data. However, it is highly improbable that every source in a wide-field survey will immediately possess the complete suite of high-resolution observables required by the diagnostic matrix. By flagging highly anomalous continuum sources in lower-resolution surveys, these algorithms can automatically trigger the deep, targeted VLBI follow-up required to confirm a candidate's astrometric and temporal technosignature credentials.

5 CONCLUSIONS

Traditional SETI strategies have emphasized the search for narrowband radio (and optical) signals because they are readily distinguishable from natural astrophysical emission. In addition, deliberately engineered narrowband beacons remain an energetically efficient and physically well-motivated signalling strategy over interstellar distances (e.g. S. Z. Sheikh et al. (2025). However, as our own technological trajectory demonstrates, advanced communication infrastructures may naturally evolve towards distributed, broad-band systems. To avoid systematically misclassifying such aggregate leakage as unstructured cosmic noise, we must expand our search parameters to identify BRaTs. This approach is complementary to conventional narrowband SETI methodologies.

We have demonstrated that a tiered hierarchical framework, utilizing deep wide-field surveys by the SKA and other wavelengths, followed by targeted global VLBI observations, provides the unparalleled sensitivity, spatial filtering, astrometric precision, and extreme brightness-temperature sensitivity required to isolate these signals.

A fundamental observational advantage of searching for BRaTs is their intrinsic insensitivity to Doppler drift. This permits arbitrarily long integrations, enabling the concept of 'SETI Deep Fields'. Such prolonged campaigns can improve sensitivity by over an order of magnitude, bringing faint Kardashev Type I planetary leakage within the detectable volume ($\lesssim$100 pc) of next-generation arrays. Furthermore, we have suggested that observing at frequencies $\gtrsim$ 1 GHz bypasses the dense ionospheric plasma barriers expected around planets orbiting active M-dwarf stars, ensuring that aggregate leakage remains visible to interstellar observers.

To distinguish candidate BRaTs from the dense population of discrete cosmic confounders such as highly compact AGN, distant SFGs, pulsars, and active local stars or magnetized exoplanets, we have presented a comprehensive multiparameter diagnostic framework. Genuine BRaTs will be identified not by a single metric, but through a distinct convergence of physical observables: extreme spatial compactness yielding $T_\mathrm{b} \gtrsim 10^6$ K, negligible polarization, engineered spectral non-uniformity, phase-stable diurnal modulation superimposed upon ISS, and sub-milliarcsecond astrometric co-motion with an offset local stellar host. We note that this framework can also be extended to Kardashev Type II civilizations, which may appear as spatially resolved, AU-scale technological aggregates.

The transition to wide-field broad-band SETI necessitates a fundamental evolution in data analysis. The sheer volume and dimensionality of next-generation astronomical surveys will require the deployment of unsupervised, AI-driven anomaly-detection pipelines. By modelling statistical representations of natural astrophysical populations, these algorithms can perform hierarchical triage, flagging multidimensional outliers to automatically trigger targeted VLBI follow-up.

Crucially, the implementation of this framework need not wait for the full deployment of the SKA. Current deep radio continuum surveys conducted by SKA precursor facilities offer an immediate opportunity to refine and deploy these diagnostic pipelines. By interrogating existing multiwavelength data sets, we can actively test this paradigm today, allowing us to place the first direct observational constraints on the prevalence and luminosity of BRaTs within the local Galactic environment.

Broadening our search strategies to include the unintentional, aggregate radio footprints of advanced civilizations represents a necessary maturation of the field. By combining the resolving power of global interferometric networks with rigorous physical diagnostics and ML, we significantly enhance our capacity to detect the complex, structured noise of technologically advanced biospheres hiding within the cosmic background.

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DATA AVAILABILITY

No new observational data were generated or analysed in support of this research. The theoretical framework and sensitivity estimates presented in this article were derived using publicly available tools, including the European VLBI Network (EVN) Sensitivity Calculator.

REFERENCES

Appleton P. N. et al., 2004, ApJS, 154, 147
Bastian T. S., Bookbinder J., Dulk G. A., Davis M., 1990, ApJ, 353, 265
Bates S. D., Lorimer D. R., Verbiest J. P. W., 2013, MNRAS, 431, 1352
Berger E. et al., 2001, Nature, 410, 338
Brzycki B., Siemion A. P. V., de Pater I., Cordes J. M., Gajjar V., Lacki B., Sheikh S., 2023, ApJ, 952, 46
Burrows A., Hubbard W. B., Lunine J. I., Liebert J., 2001, Rev. Mod. Phys., 73, 719
Chi S., Barthel P. D., Garrett M. A., 2013, A&A, 550, A68

Choza C. et al., 2024, AJ, 167, 10
Clancy P. F., 1980, J. Br. Interplanet. Soc., 33, 391
Cohen R. J., Downs G., Emerson R., Grimm M., Gulkis S., Stevens G., Tarter J., 1987, MNRAS, 225, 491
Condon J. J., 1992, ARA&A, 30, 575
Cordes J. M., Lazio J. W., Sagan C., 1997, ApJ, 487, 782
Cutri R. M. et al., 2021, AllWISE Data Release, Centre de Donnees astronomique de Strasbourg (CDS)
Dark Energy Survey Collaboration, 2016, MNRAS, 460, 1270
Deane R. P. et al., 2024, MNRAS, 529, 2428
Dennett-Thorpe J., de Bruyn A. G., 2002, Nature, 415, 57
Drake F. D., 1961, Phys. Today, 14, 40
Dulk G. A., 1985, ARA&A, 23, 169
Dyson F. J., 1960, Science, 131, 1667
Energy Institute, 2025, Statistical Review of World Energy, Energy Institute, edn., 74, London, https://www.energyinst.org/statistical-review
Enriquez J. E. et al., 2017, ApJ, 849, 104
European VLBI Network, 2024, EVN Sensitivity Calculator, https://www.evlbi.org/observing/evn-sensitivity-calculator
Fan P., Wright J., Lazio T. J., 2026, American Astronomical Society Meeting Abstracts. p. 331.03
Fender R., 2006, in Lewin W. H. G., van der Klis M., eds, Compact stellar X-ray sources, Vol. 39. Cambridge Univ. Press, Cambridge, p. 381
Frail D. A., Jagannathan P., Mooley K. P., Intema H. T., 2016, ApJ, 829, 119
France K. et al., 2016, ApJ, 820, 89
Gaia Collaboration, 2023, A&A, 674, A1
Gajjar V. et al., 2021, AJ, 162, 33
Gajjar V. et al., 2022, ApJ, 932, 81
García-Miró C., Chrysostomou A., Paragi Z., van Bemmel I., 2019, preprint (arXiv:1903.08627)
Garrett M. A., 2002, A&A, 384, L19
Garrett M. A., 2018, SETI surveys of the nearby and distant universe employing wide-field radio interferometry techniques, 68th International Astronautical Congress, IAC-18.A4.1.3, p. 2371, preprint (arXiv:1810.07235)
Garrett M. A., 2026, Acta Astron., 238, 160
Garrett M. A., Siemion A. P. V., 2023, MNRAS, 519, 4581
Garrett M. A. et al., 2001, A&A, 366, L5
Garrett M. A., Wrobel J. M., Morganti R., 2005, ApJ, 619, 105
Giulietti M. et al., 2025, A&A, 697, A81
Hallinan G. et al., 2015, Nature, 523, 568
Harris H. C. et al., 2016, AJ, 152, 118
Haykin S., 2001, Communication Systems, 4th edn. Wiley, New York
Helou G., Bicay M. D., 1993, ApJ, 415, 93
Herrera Ruiz N. et al., 2018, A&A, 616, A128
Hewish A., Bell S. J., Pilkington J. D. H., Scott P. F., Collins R. A., 1968, Nature, 217, 709
Hoare M. et al., 2015, Proc. Sci., Advancing Astrophysics with the Square Kilometre Array (AASKA14). SISSA, Trieste, PoS#115
Hori Y., 2021, ApJ, 908, 77
Ivison R. J. et al., 2010, A&A, 518, L31
Jiménez-Andrade E. F., Murphy E. J., Momjian E., Condon J. J., Chary R.-R., Taylor R., Dickinson M., 2024, ApJ, 972, 89
Kardashev N. S., 1964, Sov. Ast., 8, 217
Kelly M. C., 2009, The Earth's Ionosphere: Plasma Physics and Electrodynamics, 2nd edn. Elsevier Science
Kirkpatrick J. D., 2005, ARA&A, 43, 195
Koskinen T. T., Yelle R. V., Lavvas P., Y-K. Cho J., 2014, ApJ, 796, 16
Kraus J. D., 1973, Radio Astronomy. McGraw-Hill, New York
Loeb A., Zaldarriaga M., 2007, J. Cosmol. Astropart. Phys., 2007, 020
Lorimer D. R., Kramer M., 2012, Handbook of Pulsar Astronomy. Cambridge Univ. Press, Cambridge
Manchester R. N., Hobbs G. B., Teoh A., Hobbs M., 2005, AJ, 129, 1993
Mancuso C. et al., 2017, ApJ, 842, 95
Marcote B. et al., 2020, Nature, 577, 190
Mauduit E., Zarka P., Lamy L., Hess S. L. G., 2023, Nat. Commun., 14, 5981
McLean M., Berger E., Reiners A., 2012, ApJ, 746, 23
Messerschmitt D. G., Morrison I. S., 2012, Acta Astron., 78, 80
Middelberg E. et al., 2013, A&A, 551, A97
Miley G. K., 1971, MNRAS, 152, 477
Morrison I. S., 2012, Acta Astron., 78, 90
Murphy E. J., 2009, ApJ, 706, 482
Muxlow T. W. B. et al., 2005, MNRAS, 358, 1159
Njeri A. et al., 2023, MNRAS, 519, 1732
Paragi Z., Chrysostomou A., Garcia-Miro C., 2019, preprint (arXiv:1901.10361)
Peacock S., Barman T., Shkolnik E. L., Hauschildt P. H., Baron E., 2019, ApJ, 871, 235
Price D. C. et al., 2020, AJ, 159, 86
Radcliffe J. F., Garrett M. A., Beswick R. J., Muxlow T. W. B., Barthel P. D., Deller A. T., Middelberg E., 2016, A&A, 587, A85
Radcliffe J. F. et al., 2019, A&A, 625, C1
Radcliffe J. F., McKean J. P., Herbé-George C., Coetzer L., Matsepane T., 2025, preprint (arXiv:2504.19579)
Rampadarath H., Morgan J. S., Tingay S. J., Trott C. M., 2012, AJ, 144, 38
Remillard R. A., McClintock J. E., 2006, ARA&A, 44, 49
Rickett B. J., 1990, ARA&A, 28, 561
Rybicki G. B., Lightman A. P., 1986, Radiative Processes in Astrophysics. Wiley-VCH Weinheim, Germany
Sagan C., 1973, Icarus, 19, 350
Saide R. C., Garrett M. A., Heeralall-Issur N., 2023, MNRAS, 522, 2393
Schwartz R. N., Townes C. H., 1961, Nature, 190, 205
Sheikh S. Z., Wright J. T., Siemion A., Enriquez J. E., 2019, ApJ, 884, 14
Sheikh S. Z., Huston M. J., Fan P., Wright J. T., Beatty T., Martini C., Kopparapu R., Frank A., 2025, AJ, 169, 118
Shu F. H., Adams F. C., Lizano S., 1987, ARA&A, 25, 23
Stirling A. M., Spencer R. E., de la Force C. J., Garrett M. A., Fender R. P., Ogley R. N., 2001, MNRAS, 327, 1273
Sullivan III W. T., Brown S., Wetherill C., 1978, Science, 199, 377
Suresh A. et al., 2023, AJ, 165, 255
Tellis N. K., Marcy G. W., 2017, AJ, 153, 251
Testi L. et al., 2015, Proc. Sci., Advancing Astrophysics with the Square Kilometre Array (AASKA14). SISSA, Trieste, PoS#117
van der Kruit P. C., 1973, A&A, 29, 263
Verschuur G. L., 1973, Icarus, 19, 329
Villadsen J., Hallinan G., 2019, ApJ, 871, 214
Wandia K. et al., 2023, MNRAS, 522, 3784
Williams R. E. et al., 1996, AJ, 112, 1335
Zarka P., 1998, J. Geophys. Res., 103, 20159
Zarka P., 2007, Planet. Space Sci., 55, 598
Zuckerman B., 2026, ApJ, 1001, 167

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