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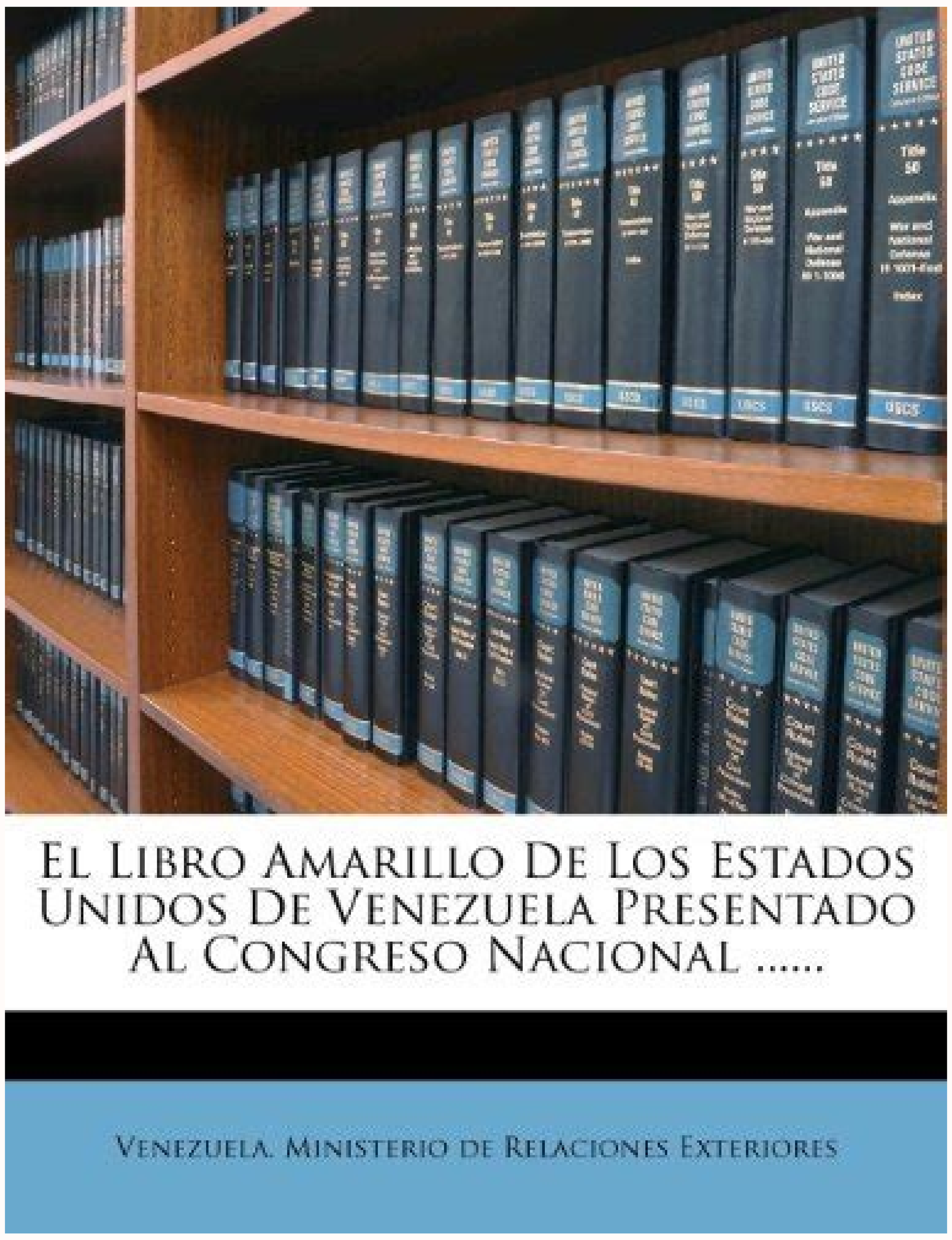

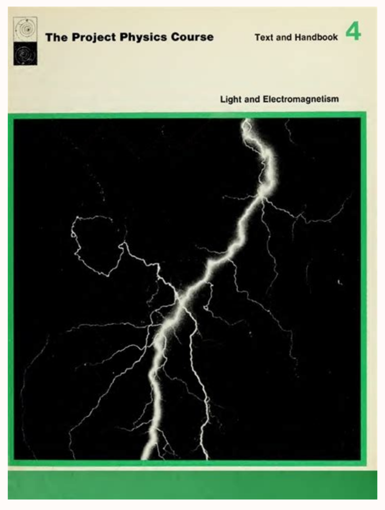

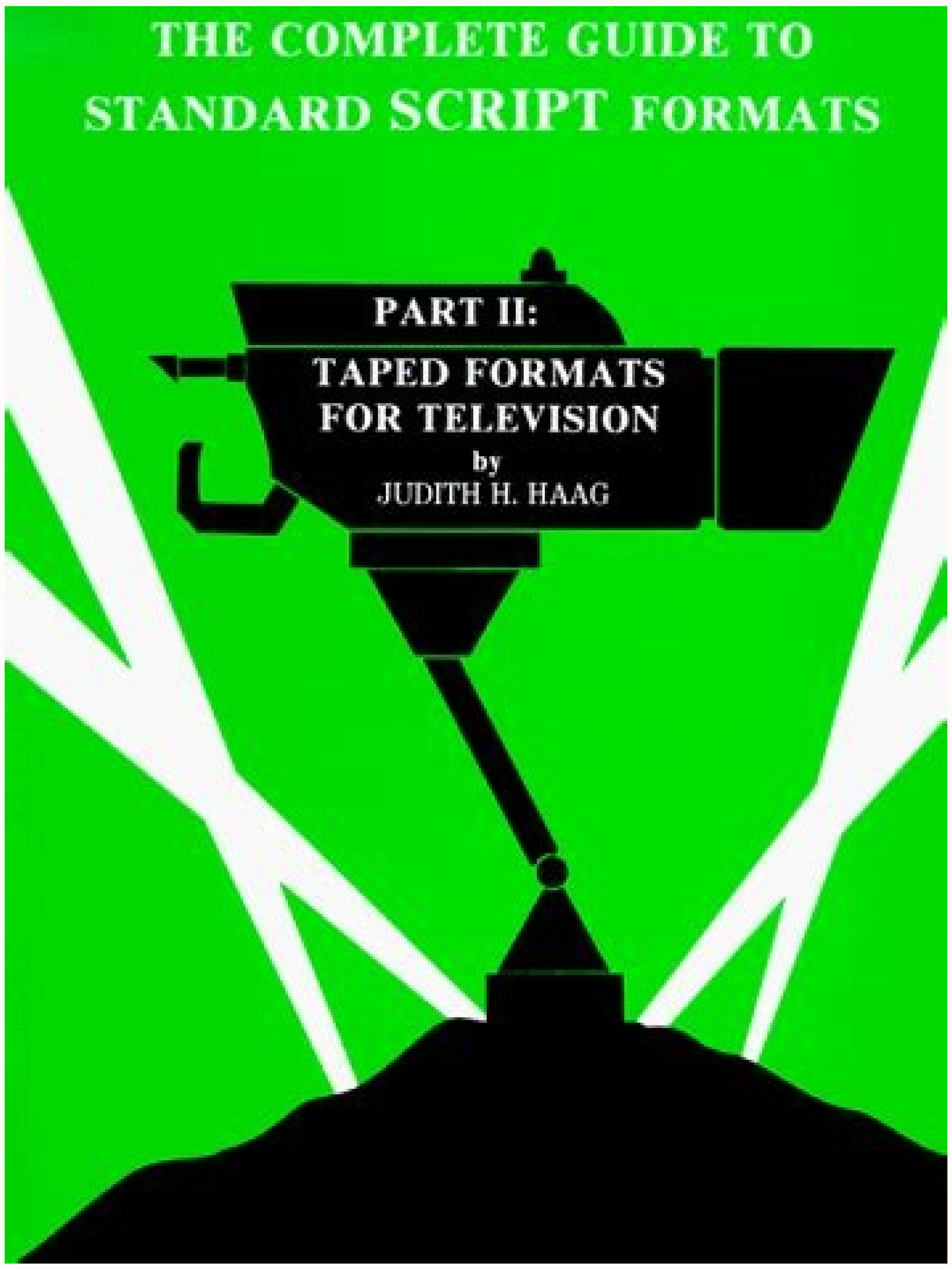

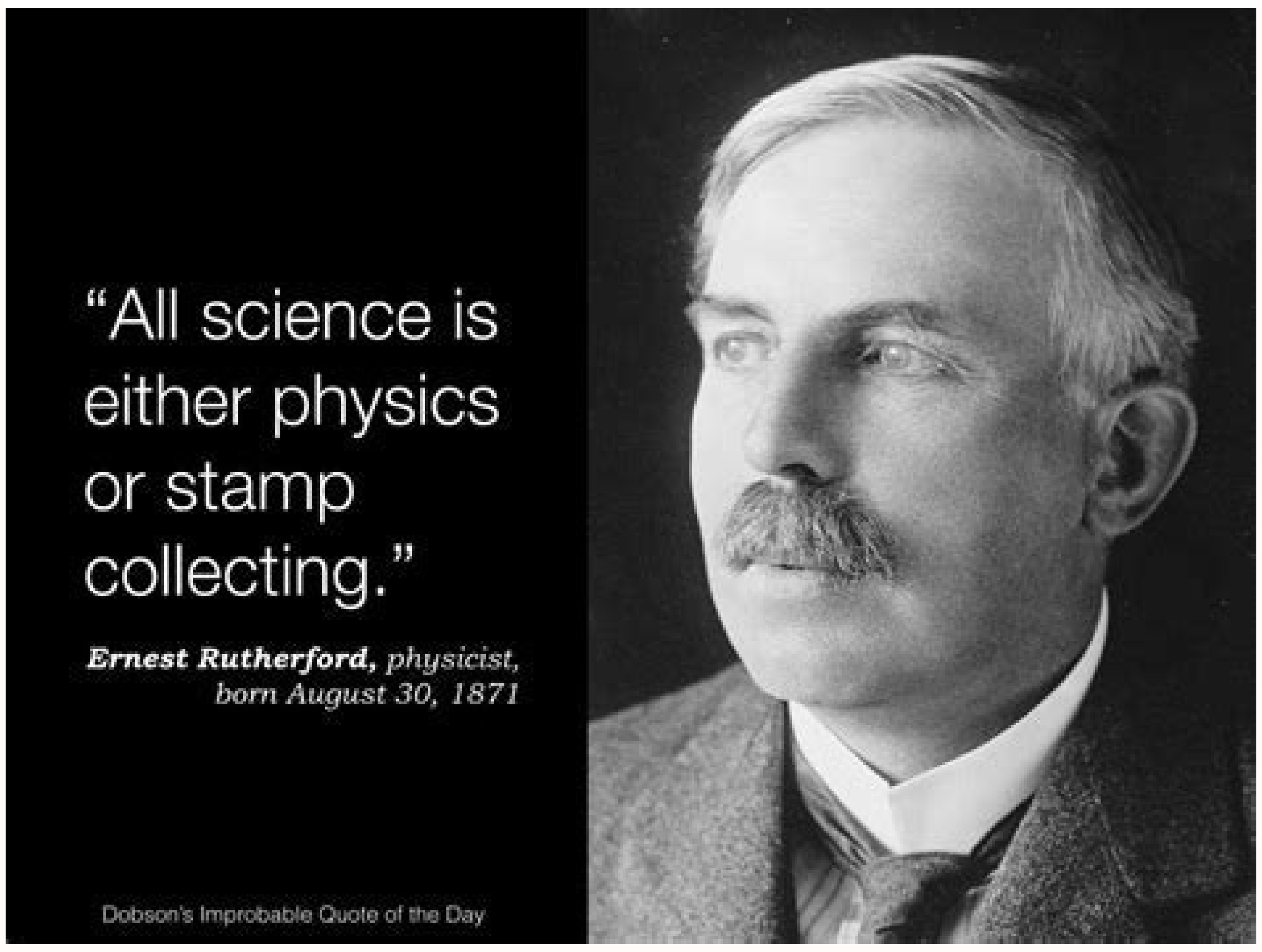

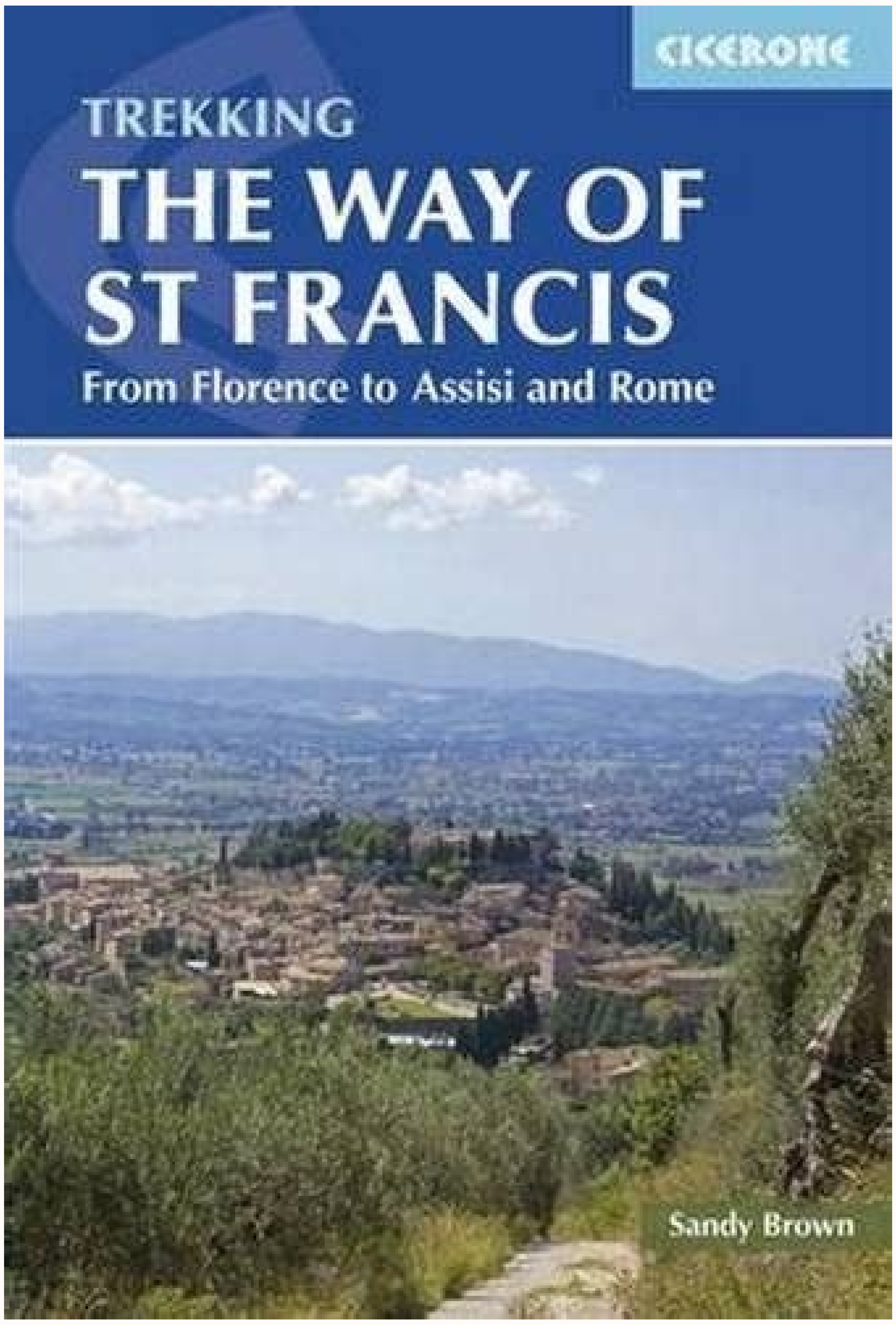

(2005) suggest that BH-LM-XRBs may actually dominate XRB-CR production despite the fact that they are less numerous in the Galaxy. 4.2 Calculating maximum energy The time-scales of interest in computing the maximum energy are as follows: $$\begin{eqnarray*} t_{\rm acc}^{-1} = \dfrac{\eta e c B }{E} , \end{eqnarray*}$$(12) $$\begin{eqnarray*} t_{\rm sync}^{-1} = \dfrac{4}{3} \left (\dfrac{m_\mathrm{ e}}{m_\mathrm{ p}}\right)^3 \, \dfrac{c \, \sigma _\mathrm{ T} \, U_\mathrm{ B} }{m_\mathrm{ e} c^2} \dfrac{E}{m_\mathrm{ p} c^2} , \end{eqnarray*}$$(13) $$\begin{eqnarray*} t_{\rm adi}^{-1} = \dfrac{2}{3} \dfrac{\beta }{z} . Once these upgrades are realized, XRB systems such as Cygnus X-1 will be key targets for neutrino observatories to test whether XRB jets are important CR accelerators. Comparatively, XRBs with HM secondaries tend to persistently accrete matter via strong stellar winds (with some notable exceptions; see e.g. Tetarenko et al. 2015; Zanin et al. 2002). (2018) suggest that between 300 and 1000 BH-XRBs exist in the GC. Observations of such clouds can be used to constrain the low-energy CR flux in the surrounding region. Here, we neglect proton–photon interactions. The higher the initial aspect ratio, the wider the jet, and thus the particles are confined more easily at high jet heights; the smaller the βp value, the higher the magnetic field strength, which results in smaller Larmor radii, aiding confinement, but producing larger synchrotron losses. Although XRB-CRs might dominate the parts of the CR spectrum, this is highly dependent on the total CR power, maximum energy of individual CRs, and the acceleration power-law index. The quasi-isothermal agnjet model used in Fig. 4 is not a conical model but instead considers self-collimation. Given our results, we suggest that in the most optimistic case XRB-CRs might dominate (or contribute significantly to) the spectrum close to 1017 eV, near the second knee, where a light-mass component has been detected (Pierre Auger Collaboration 2014; Buitink et al. For instance, in Buitink et al. 2012). We can approximate to $$\begin{eqnarray*} \omega (z) = n m_\mathrm{ p} c^2 + \Gamma _{\rm adi} U_\mathrm{ j} , \end{eqnarray*}$$(7)where we have assumed the jet can be treated as an ideal gas with adiabatic index, Γadi, as in Falcke & Biermann (1995). This gives us one-fourth of the available power for hadronic acceleration, multiplied by 2 as there are two similar jets in each system. Phys., , 10.1088/1475-7516/2017/02/015 , , , , , , , , , , , The Origin of Cosmic Rays. The GC molecular cloud Sgr B2’s X-ray emission has been decaying over the last two decades, which is primarily due to X-ray echo of past activities of Sgr A⋆ (Inui et al. The subdominant, higher maximum energy component has approximately 10 per cent of the power of the low-energy source, in agreement with most optimistic findings of total XRB-CR power in Section 3. However, the number of BH-LM-XRBs in the Milky Way is poorly constrained, with population synthesis predictions ranging from 102 to 105 (e.g. Pfahl, Rappaport & Podsiadlowski 2003; Kiel & Hurley 2006; Yungelson et al. In particular, we show (green dashed line) the maximum allowed contribution, which is calculated by taking the upper parameters in Table 1. In table 15 of Tetarenko et al. \end{eqnarray*}$$(A1)The Euler equation is $$\begin{eqnarray*} \left (\gamma _\mathrm{ j} \beta _\mathrm{ j} \dfrac{\Gamma _{\rm adi} + \xi }{\Gamma _{\rm adi} - 1} - \Gamma _{\rm adi} \gamma _\mathrm{ j} \beta _\mathrm{ j} - \dfrac{\Gamma _{\rm adi}}{\gamma _\mathrm{ j} \beta _\mathrm{ j}} \right) \dfrac{\partial \gamma _\mathrm{ j} \beta _\mathrm{ j} }{\partial z} = \dfrac{2}{z} , \end{eqnarray*}$$(A2) $$\begin{eqnarray*} \xi = \dfrac{1}{\zeta } \left (\gamma _\mathrm{ j} \beta _\mathrm{ j} \sqrt{\dfrac{1 + 2 \zeta \Gamma _{\rm adi} - \zeta \Gamma _{\rm adi}^2}{\zeta \Gamma _{\rm adi} (\Gamma _{\rm adi} - 1)}} \,\, \right)^{\Gamma _{\rm adi}-1} \left (\dfrac{z}{z_0}\right)^{2 (\Gamma _{\rm adi} -1)} . To estimate the realistic range of values of |$L_\mathrm{ CR}$|, we use plausible ranges for each parameter. $$\begin{eqnarray*} U_\mathrm{ j}(z) = \zeta n_0 m_\mathrm{ p} c^2 \left (\dfrac{\gamma _\mathrm{ j} \beta _\mathrm{ j}}{\gamma _0 \beta _0}\right)^{-\Gamma _{\rm adi}} \left (\dfrac{z}{z_0}\right)^{-2} . This results in a slightly different jet radius profile: $$\begin{eqnarray*} r_{\rm coll}(z) = r_0 + (z - z_0) \dfrac{\gamma _0 \beta _0}{\gamma _\mathrm{ j} \beta _\mathrm{ j}} . Tetarenko for helpful discussions. \end{eqnarray*}$$(11)This gives us a slightly narrower jet for larger values of z.When we calculate the maximum energy of accelerated CRs in the jet, we vary both r0 and βp. In the following, we look to the inner 200 pc of the Galaxy to constrain the power of Galactic XRB jets as CR sources. 639.043.513. Furthermore, KM3-NET upgrades over the next decade will increase the angular resolution of detections to 1 GeV) ≤ (1.3–39) × 1038 erg s−1, where the range of values reflects the allowed ranges of both the Emin parameter and low-energy CR power constraints described in Section 3.1.2. As the analytical and numerical analysis of the HESS data suggests an upper limit of LCR(>1 GeV) ∼ 1038 erg s−1, we find that the HESS γ-ray measurements better constrain the CR power in the region, assuming α = 2.2. However, softer CR injection spectra or alternative contributions to the observed γ-rays in region would mean the low-energy constraints are more stringent limits. 36th Int. XRB jets are fed from accretion discs and stellar winds, presumably hadron-rich environments, yet the composition of XRB jets is still unclear. 2006; Sadowski et al. In particular, based on recent NuSTAR observations, Hailey et al. We estimate the proportion of the binaries that are actively transferring mass via Roche lobe overflow by counting only those systems in which the radius of the main-sequence star extends beyond the first Lagrangian point, L1, of the system. To this end, indirect ‘smoking gun’ signals, including characteristic TeV γ-ray spectra from pion decay channels, can be observed to verify CR acceleration sites. SM was supported by an NWO (Netherlands Organisation for Scientific Research) VICI award, grant no. This is consistent with our total XRB-CR power derived earlier in this section. However, in the recent years, as the X-ray echo component further faded away, Sgr B2’s X-ray emission seemed to enter a constant low-flux stage, which is interpreted as GeV CR illumination. Together these two results indicate that XRB-CRs could even dominate the total CR spectrum in part of the transition region between SNR-CR and extragalactic CR components, above the knee and below the ankle, in broad agreement with recent mass composition results. Given the average gas density in the CMZ and a typical size of the region H ≃ 100 pc, we get $$\begin{eqnarray*} L_{\gamma } (\gt \!200 \,{\rm GeV}) = 1.2 \times 10^{36} \, {{\rm erg}\,\mathrm{ s}^{-1}} \left(\frac{L_{\rm CR}}{1.6 \times 10^{39} \, {{\rm erg}\,\mathrm{ s}^{-1}}} \right) . In Fig. 1, we show a schematic of the all-particle CR spectrum, with a range of allowed contributions from the XRB-CR component calculated in this work. Although these systems currently seem to be mostly in quiescence, they could have been more active in the past. From equations (5)–(7), we see that the value of Lj(z0), the power at the base of the jet, depends on n(z0) and Uj(z0), the number density and internal energy density at the base of the jet. (2005), using an outburst-oriented approach to incorporate advances in recent population studies, particularly the Watchdog data base3 (Tetarenko et al. One can assume that in the confinement-limited region, accelerated CRs that exceed the critical energy at which the particle stays confined escape the jet to propagate through the ISM.We find that the maximum attainable CR energy depends strongly on geometry, jet model, and acceleration region, but in general protons can reach energies of 1016–1017 eV if accelerated with a canonical efficiency of η = 0.1 (Caprioli & Spitkovsky 2014). Models of jet emission therefore require very high energy electrons as sources of X-ray and γ-ray emission (e.g. Markoff, Nowak & Wilms 2005; Bosch-Ramon, Romero & Paredes 2006; Zdziarski et al. Thermal–viscous instabilities developing within the accretion disc give rise to outburst cycles (e.g. Lasota 2001). A2. In order to estimate the γ-ray emission from a population of cosmic particles injected by a cusp of XRBs located in the inner Galaxy, we perform both an analytical estimate and a numerical simulation.For the analytical order-of-magnitude estimate, we follow the approach described in detail in Jouvin et al. 2009; Terrier et al. Astropart. \end{eqnarray*}$$(15)The condition for confinement can be rewritten from Hillas’ seminal paper (Hillas 1984) as $$\begin{eqnarray*} E_{\rm CR}(z) \lt \dfrac{B(z)}{\mu \mathrm{ G}} \times \dfrac{R(z)}{\mathrm{ pc}} \times \dfrac{\beta }{0.5} \times 10^{15} \, {\rm eV} . We would also like to thank the anonymous referee for their thorough and insightful comments that improved this work. In the context of the SNR hypothesis, one of the key ideas to explain the knee and second knee features is rigidity-dependent diffusive shock acceleration, in which the maximum possible energy of a given CR species depends on its atomic number Z such that Emax(Z) = Z × Emax(1). Lastly, we note that in specific geometries and acceleration regions CR energies higher than 1017 eV could be reached, but this might only be plausible in atypical systems such as very powerful, wide, or highly magnetized jets. By considering only the hard, compact jet state, we can obtain a conservative lower limit of |$L_\mathrm{ CR}$|. However, given the comparatively short lifetime of the intermediate compared to hard accretion states in BH-LM-XRBs (i.e. tIMS ∼ 1–10 d, tHS ∼ 20–50 d; Tetarenko et al. 2017). The jet is fed by the disc and the power of the jet at a height z is given by $$\begin{eqnarray*} L_\mathrm{ j}(z) = \Gamma _\mathrm{ j}^2 \beta _\mathrm{ j} c \omega \pi z^2 \sin ^2(\theta) , \end{eqnarray*}$$(5)where Γj(z) is the Lorentz factor of the bulk jet flow, z is the height of the jet above the BH (z0 is the height of the jet base), and ω(z) is the enthalpy. Vol. 2003; Falcke et al. 6 CONCLUSION We have suggested that XRB jets could accelerate protons to high energies, similar to their larger counterparts in AGNs. Within the uncertainties allowed by current population models, jet composition, and GC observational constraints, a total XRB-CR power of between 1036 and 1039 erg s−1 is possible. This means that r0 is an important free geometric parameter, which sets the initial radius of the jet. Realistically, particle acceleration is also expected in other accretion states. These equations are valid for all jet models considered in Appendix A.To compute radiative losses and confinement of accelerated CRs in the jet, the most important parameters are the jet radius, R(z), and the magnetic field strength, B(z). Observations of the Sgr B2 molecular cloud using NuSTAR in 2013 have shown that, after more than 10 yr of flux decaying, the remaining X-ray emission from Sgr B2 is consistent with the GeV CR illumination scenario (Zhang et al. Observational evidence of Doppler shifted atomic line emission at relativistic velocities (Margon et al. The internal energy density profile is $$\begin{eqnarray*} U_\mathrm{ j}(z) = \zeta n_0 m_\mathrm{ p} c^2 \left (\dfrac{\gamma _\mathrm{ j} \beta _\mathrm{ j}}{\gamma _0 \beta _0}\right)^{-\Gamma _{\rm adi}} \left (\dfrac{z}{z_0}\right)^{-2 \Gamma _{\rm adi}} . 1979; Migliari, Fender & Méndez 2002; Díaz Trigo et al. \end{eqnarray*}$$(A8)The figure for this jet model is found in Section 4, Fig. 4. In the most intriguing scenario, XRB-CRs could dominate the observed spectrum above the so-called knee feature at ∼3 × 1015 eV, offering an explanation for several key issues in this transition zone from Galactic to extragalactic CRs. We discuss how such a scenario could be probed in the near future via multimessenger observations of XRB jets, as well as diffuse Galactic neutrino flux measurements. 2005; Bordas et al. As diffuse neutrino limits are already encroaching on best models of neutrino emission from Galactic CRs, the 10-fold detector volume increase specified for IceCube-Gen2 will probe our predictions of a break in the Galactic neutrino spectrum due to a high-energy Galactic component. 2006). 4 MAXIMUM ENERGY OF XRB-CRs We have shown that BH-XRBs can viably contribute a significant fraction of the total Galactic CR power without violating constraints in the GC, so we now consider the maximum energy attainable by XRB-CRs.The maximum energy of accelerated CRs in jets is limited either by energy losses (synchrotron, inverse Compton, and adiabatic losses are the primary channels) or by the Hillas criteria for confinement (Hillas 1984). CTA will thus likely be able to detect and identify the Galactic PeV BH-XRB sources in the near future (Kantzas et al., in preparation).As a consistency check, we again used the dragon code to look at the expected diffuse Galactic γ-ray emission due to the XRB population. Open in new tabDownload slideMaximum proton energy as a function of distance from the base of the jets for a quasi-isothermal jet model, where we use η = 0.1. We vary two important parameters: initial aspect ratio |${r_0}/{z_0}$| in orange and plasma |$\beta _\mathrm{ p} = {U_{\mathrm{ e}+\mathrm{ p}}}/{U_{\mathrm{ B}}}$| in blue. Parameter . Upper . Middle . Lower . A 0.3 0.1 6 × 10−3 |$\dfrac{L_\mathrm{ X}}{L_{\mathrm{ edd}}}$| 0.05 0.03 0.01 N 104 3 × 103 103 The fraction of an XRB jet’s total power transferred to CR acceleration, the CR luminosity |$L_{\mathrm{ CR}}$|, also involves many parameters lacking strict uncertainties. This is especially true for BH-LM-XRB systems where the LM companions are expected to have relatively modest photon field contributions. Coupled with greater sensitivities, point source neutrino astronomy will soon be at the forefront of identifying CR sources within our Galaxy. This range of values falls within our estimates for the total XRB-CR power as found earlier, representing 0.1–10 per cent of the total Galactic CR power. The components are SNR-CRs (red), X-ray binary (XRB)-CRs (this work; green), and a canonical extragalactic component (yellow). 2004), Fender et al. Possible candidates for such high-energy Galactic components include strong Galactic winds (Jokipii & Morfill 1987), newborn pulsars (Fang, Kotera & Olinto 2013), Galactic γ-ray bursts (Levinson & Eichler 1993), Wolf–Rayet star supernovae (SNe; Thoudam et al. Given our population synthesis analysis, the density cusp in the Galactic Centre (GC), and the uncertainties involved, we suggest 104 is a reasonable upper limit for the Galactic XRB population, as reflected in Table 1. While this data set is the most complete to date with respect to XRB duty cycles, the mean duty cycle derived has to be considered as an upper limit, by virtue of the fact that only systems that have gone into outburst at least once are counted. (2005), to evaluate the XRB jet power from X-ray observations. When observed in the X-ray waveband, an LM-XRB will evolve through a number of distinct accretion states defined by the source spectrum and luminosity (Remillard & McClintock 2006). Such particle acceleration may occur at any point along the jets, and the signature flat/inverted radio spectra suggest that continuous re-acceleration of radiating particles is required throughout the jet to combat adiabatic losses (Blandford & Königl 1979; Malzac 2014; Péault et al. By considering the global energetics and estimating the proportion of power available for CR acceleration, we can estimate the CR flux and evaluate whether XRBs could reasonably account for a significant Galactic CR contribution.XRBs come in four varieties, categorized by the compact object [either a BH or neutron star (NS)] and the companion star [low mass (LM) or high mass (HM)]. Gabici, D. For more details regarding the analytical estimate, we refer to section 2 in Jouvin et al. 5.1 γ-rays Several XRB jets are now known to emit γ-rays (Tavani et al. However, alternative models also exist, mostly based on the assumption of energy-dependent leakage of high-energy CRs from the Galaxy (see for instance, Giacinti, Kachelrieß & Semikoz 2015), which look to negate the need for an extragalactic CR component to dominate down to the second knee. We assume a low-energy component that saturates the observed CR spectrum below the knee, as expected by the dominant Galactic CR source. In all other models, losses are compensated for by continuous re-acceleration of particles. CR paths are deflected in the Galactic magnetic field and therefore we cannot directly trace them back to their source. These calculations assume protons (i.e. Z = 1), but if more massive CR ions are present in the jet they would attain greater energies as the maximum CR energy scales with rigidity. (2018) population derived in this work. 2009; Russell et al. In the isothermal model, adiabatic losses are fully compensated for, whereas in the quasi-isothermal models only longitudinal (z-direction) losses are compensated for. The total low-energy CR power upper limit of (0.4–2.3) × 1039 erg s−1 applies to CR energies between Emin = 1–100 MeV and Emax = 1 GeV, i.e. the model parameters used by Zhang et al. \end{eqnarray*}$$(A4)The Euler equation is $$\begin{eqnarray*} \left (\gamma _\mathrm{ j} \beta _\mathrm{ j} \dfrac{\Gamma _{\rm adi} + 1 }{\Gamma _{\rm adi} - 1} - \Gamma _{\rm adi} \gamma _\mathrm{ j} \beta _\mathrm{ j} - \dfrac{\Gamma _{\rm adi}}{\gamma _\mathrm{ j} \beta _\mathrm{ j}} \right) \dfrac{\partial \gamma _\mathrm{ j} \beta _\mathrm{ j} }{\partial z} = \dfrac{2}{z} . 2016a) and thus have somewhat more continuous outflows. This results in a jet base magnetic field strength, B(z0), of (5–10) × 106 G, in line with other models (Romero & Vila 2008; Pepe et al. Given the transient nature of some of these sources (and especially the complex environment of the SS 433 system), we do not necessarily expect CR acceleration and subsequent γ-ray emission continuously from XRB systems. As mentioned in Section 4, we believe that for XRB jets, the quasi-isothermal jet model is the most appropriate.From this starting point, assumptions about the physics of the jet lead to different models. In Appendix A, we provide an overview of the different jet models and the parameters involved in computing the maximum CR energy. \end{eqnarray*}$$(9)βp is an important free parameter that sets how energy is distributed among particles and magnetic fields, and we show how different values of βp affect the maximum CR energy in Fig. 4.The prescription of Uj(z) depends on the choice of jet model as shown in Appendix A. While we take 103 as a conservative lower estimate for the total number of Galactic BH-LM-XRBs in this work, we note that only ∼60 BH-XRBs have been (observationally) confirmed to exist in the Galaxy.2 Thus, the true Galactic BH-LM-XRB population remains a major source of uncertainty in our calculations. Cosmol. Therefore, the clear detection of a component associated with the Galactic plane may be round the corner (see for instance, a recent 2σ hint reported in Aartsen et al. In each case, we briefly explain the assumptions and list the Euler equation for the model. If we conservatively assume that CR acceleration in the jets of these systems is responsible for all of the observed γ-ray flux in HESS Collaboration (2016), we can constrain the maximum CR power per system to be 1034 ≲ LCR ≲ 3 × 1035 erg s−1. , Cherenkov Telescope Array Consortium, , Science with the Cherenkov Telescope Array. (2018) population.

All the XRBs found in the data sets had main-sequence stars of less than 10 M⊙ and so can be in general considered BH-LM-XRBs.Recent observations suggest many more such systems may exist in the Galaxy than previously thought (Corral-Santana et al. We stress that this is an upper limit based on the entire γ-ray flux as observed by HESS Collaboration (2016) to originate from CRs accelerated in jets of the density cusp of XRBs in the GC, and is primarily used as a sanity check to ensure our assumptions do not violate observational limits. Kantzas, and B. We plot different maximum energy cut-offs, as the maximum CR energy for each source is not well known. However, it is not immediately clear how many of these systems are actively transferring mass and could therefore be classed as XRBs. To understand this, we used the synthetic BH catalogue data base provided by Olejak et al. A2 Isothermal jet model In the isothermal jet model, all adiabatic losses are recompensated for and thus Tj is constant. , , , Proc. However, the current limits from a joint analysis of ANTARES and IceCube data (Albert et al. Lastly, we suggest multimessenger possibilities to confirm XRB-CR (or generic second Galactic components) through diffuse neutrino and γ-ray measurements of our Galaxy, as well as point source observations. One possibility is that the extragalactic component is dominant all the way down to 1017 eV, requiring the ankle feature to be a peculiar extragalactic propagation effect. In particular, the origin of CRs between second knee and ankle, and the location of the transition from Galactic to extragalactic CRs remain unclear. Although observations of X-ray filaments (Vink & Laming 2003) and γ-ray spectra from old SNRs (Ackermann et al. 2017a; MAGIC Collaboration 2018). This is to say that the most powerful XRB jets may be capable of producing higher energy CRs than outlined here. Ray Conf. The observed spectrum follows a power law with an index of p ≈ −2.7 over many decades of energy. In general, the maximum energy is limited by radiative losses at lower jet height due to strong magnetic fields, and is confinement limited at large z.In general, models of jets are based on the jet–disc symbiosis ansatz laid out in Falcke & Biermann (1995). Furthermore, the average outburst duration (months to years) is still somewhat comparable to the total on-time of 19 yr, which makes rigorous statistical statements difficult. The origin of cosmic rays (CRs), high-energy particles from beyond the Solar system, is a century-old puzzle (Ginzburg & Syrovatskii 1964; Berezinsky et al. 5.2 Neutrinos Neutrinos are also produced through CR interactions with protons or photons, and XRB jets have long been predicted as a sources of neutrinos (Levinson & Waxman 2001; Distefano et al. The γ-ray flux is integrated over the region of interest defined in figs 1 and 3 of HESS Collaboration (2016); the HESS data are shown as red triangles.Hailey et al. As discussed earlier, HM companions are rarer and live shorter lives, and likely make up a minority of BH-XRB systems.Of the transient systems, we find mean and median number of days spent in the hard state of 183 and 66 d, respectively (see Fig. Protons/ions present in the jets will also undergo shock acceleration and in fact would attain much higher energies than electrons due their lower cooling efficiency compared to leptonic counterparts. We note that Uj(z) is very similar for the isothermal and quasi-isothermal models, as only the dependence on the radius is different. (2016a), in which the authors catalogued X-ray observations of all known BH-XRBs over the last 19 yr. In light of increasingly detailed multiwavelength studies of many more XRB jets (Corral-Santana et al. Therefore, BHs, which generally require more massive progenitors, are less common than NSs. Thus, we expect many more NS-XRBs than BH-XRBs, as well as more systems with LM companions than HM companions. Czech., , , , , , , , , , , , , , , , , , in , , , , , eds, AIP Conf. 2017), for different values of the initial aspect ratio, |${r_0}/{z_0}$|, and βp of the jet.Radiative losses dominate near the BH, as the high magnetic field strength close to the base of the jet results in large synchrotron losses. Cosm. A key difference here is that we include self-collimation, and so the radius of the jet as a function of jet height z is given by equation (11). Such γ-ray flux clearly saturates the γ-ray emission reported by the HESS Collaboration (see Fig. 3); thus, we confirm the analytical order-of-magnitude estimate for the upper limit on the power injected in CRs at the GC from an XRB population. 2013) suggest that protons are efficiently accelerated at these sources, it is not clear whether SNRs can universally attain the crucial PeV energies required to explain the softening at the knee (see e.g. the recent discussion in Gabici, Gaggero & Zandanel 2016; Ahnen et al. (ICRC 2019), , , IceCube-Gen2 Collaboration, , , , , , , , , , , Pierre Auger Collaboration, , Pierre Auger Collaboration, , , , , Bull. This means that |$T_\mathrm{ j} \propto n^{\Gamma _{\rm adi} - 1}$|. If this population of BH-XRBs is similar to the broader Galactic population in their potential to accelerate CRs, we expect to see γ-ray signatures of this in the region. The maximum energy CR energy as a function of jet height can be seen in Fig. Most pertinent for our study, we find the number of days each system has spent in the hard, compact jet state, which is invaluable to constrain the hard state duty cycle. Such a contribution would make up a significant fraction of the CRs in the energy range between second knee and ankle, where the role of a second Galactic component is currently under debate. The maximum energy of XRB-CR is relatively high compared to other Galactic sources of CRs, with models suggesting protons could be accelerated to 1016–1017 eV in some systems. 1990; Blasi 2013). 2017) and gammasky. Using these codes, we are able to propagate CRs from any given source distribution and, adopting detailed models for the gas and interstellar radiation in the Galaxy, compute the γ-ray/neutrino flux associated with the CR population under consideration. The observation of diffuse γ-ray emission in a region can therefore tell us about the density of both the ambient medium and high-energy CRs in that region. Astron. 2006; Plotkin et al. We set a hard injection spectrum described by a single power law Q = Q0(E/E0)−α, with α = 2.2 and Emin = 1 GeV, and let the particles propagate through the CMZ and diffuse out of the Galaxy.After the equilibrium distribution of CRs is obtained, we compute the hadronic γ-ray flux from the Galactic ridge region with the gammasky code, adopting the same model for the gas distribution in the CMZ as in Gaggero et al. 2006) that may accelerate CRs. 3.1 Constraints from Galactic Centre observations Galactic CRs propagate from their sources interacting with interstellar gas to produce γ-rays and neutrinos. (2018) population are the only sources of CRs that contribute to the X-ray illumination.GeV CR protons/ions bombarding giant molecular clouds produce X-ray emission through collisional ionization and bremsstrahlung. This means that Up ∝n, and energy is not conserved. This is to say that accelerated CRs must stay confined within the accelerating medium in order to undergo re-acceleration, which we can quantify using the Larmor radius. We are yet to firmly identify classes of astrophysical sources able to accelerate hadronic cosmic particles up to extremely high energies, much larger than those accessible by terrestrial accelerators.Spectral features in the locally observed all-particle CR spectrum can shed light on this mystery. We set up the dragon code to inject CRs with a Gaussian source term centred on the GC with a 1 pc width, consistent with the Hailey et al. It directly influences the extent to which high-energy CRs can be confined, resulting in further acceleration. The conservative upper limit on this quantity is |$L_{\rm CR} \sim 10^{38} \, {\mathrm{ erg}\,\mathrm{ s}^{-1}}$|. For the isothermal and adiabatic jet models, we use a simple conical jet model in which $$\begin{eqnarray*} r_{\rm cone}(z) = r_0 + (z - z_0) \sin (\theta) . The former relies on understanding the population and energetics of typical systems. The Euler equation, however, includes an additional factor: $$\begin{eqnarray*} \left (\gamma _\mathrm{ j} \beta _\mathrm{ j} \dfrac{\Gamma _{\rm adi} + \xi }{\Gamma _{\rm adi} - 1} - \Gamma _{\rm adi} \gamma _\mathrm{ j} \beta _\mathrm{ j} - \dfrac{\Gamma _{\rm adi}}{\gamma _\mathrm{ j} \beta _\mathrm{ j}} \right) \dfrac{\partial \gamma _\mathrm{ j} \beta _\mathrm{ j} }{\partial z} = \dfrac{2}{z} , \end{eqnarray*}$$(A7) $$\begin{eqnarray*} \xi = \dfrac{1}{\zeta } \left (\dfrac{\gamma _\mathrm{ j} \beta _\mathrm{ j}}{\gamma _0 \beta _0}\right)^{\Gamma _{\rm adi} -1} . For more on the jet models, please see Appendix A. Future Sgr B2 X-ray observations will put a tighter constraints on the required CR proton power in the CMZ. 2009), and recently SS 433, which was resolved in the TeV range (HAWC Collaboration 2018; Sudoh, Inoue & Khangulyan 2020). 2). 2014; Zdziarski et al. (2015). As the magnetic field strength depends strongly upon the internal energy density of the jet, Uj, the maximum CR energy increases significantly for higher jet powers. Here, we give a quick overview of each jet model, and show how the maximum CR energy depends on the jet model. (2005). For each of these systems, we looked up the binary separation, a, and approximated the radius of the main-sequence star from its mass. Using this, we extrapolate to find an allowed high-energy XRB-CR power due to the Hailey et al. We adopt the method used in Fender et al. Comparing the expected emission from CR-accelerating XRBs in the GC to the observed emission, we can constrain the CR power of these systems, and thus by extrapolation gain an additional constraint on the Galactic population as a whole. The dashed green line represents the upper limit of the allowed XRB-CR power as discussed in Section 3, using the upper parameters in Table 1. 2016), we can probe PeV energy ranges in order to verify whether there are two clear populations of high-energy CR sources within our Galaxy. 2014).Although leptonic processes such as inverse Compton scattering might be the dominant mechanism for such high-energy emission, hadronic particles may also significantly contribute. We focus on the energy budget available for CR acceleration in all Galactic XRB jets and the maximum energy these XRB-CRs could attain, as these are the crucial inputs to determine a potential CR contribution. Taking the mean and median number of days divided by the total time in which the data were collected (19 yr) as the duty cycle of these systems, we compute hard state duty cycles of 2.6 and 1.0 per cent, respectively. 2019), and diffuse Galactic searches could provide indeed a novel approach towards identifying a second source of Galactic CRs. Neutrino observations probe higher energies than γ-ray facilities and therefore high-energy breaks in the diffuse Galactic neutrino spectra (Aartsen et al. 4.1 Jet model We calculate the maximum energy of accelerated protons for the three different dynamical jet models (isothermal, adiabatic, and quasi-isothermal agnjet variant) outlined in Crumley et al. Open in new tabDownload slideγ-ray spectral energy distribution associated with the population of CRs accelerated by XRBs located at the GC. 2018). This factor is the average amount of time a BH-XRB spends in the hard state, the state in which we expect steady, compact jets that efficiently accelerate particles.To estimate δt, we utilize the data collected in Tetarenko et al. It is important to note that although almost 25 per cent of all BH-XRBs seem to be persistent accretors with HM companions, this is likely inflated due to observational bias due to their persistent and thus more reliably detected emission. (2016), a novel data set based on 150 d of radio observations of CR-induced extensive air showers made with the Low-Frequency Array implies a significant light-mass component in the 1017−1017.5 eV range. Taking this additional component into account, as discussed in Hillas (2005) and Gaisser, Stanev & Tilav (2013), it is possible to provide a complete and consistent description of all the features from the knee to the ankle. 5 MULTIMESSENGER TESTS OF THE XRB-CR SCENARIO Any source class contribution to the CR spectrum can only be directly probed by CR observatories if those sources dominate the spectrum at specific energies. Therefore, we suggest point source γ-ray observations of the most powerful XRB jets will pave the way for identifying CRs from XRBs through traditional electromagnetic observations. 2019), the A-parameter normalization estimated by Fender et al.