Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **466,** 2922–2926 (2017) doi:10.1093/mnras/stw3337
Advance Access publication 2016 December 23

Ultrahigh-energy cosmic ray hotspots from tidal disruption events

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Accepted 2016 December 19. Received 2016 December 19; in original form 2016 January 15

ABSTRACT

We consider the possibility that tidal disruption events (TDEs) caused by supermassive black holes (SMBHs) in nearby galaxies can account for the ultrahigh-energy cosmic ray (UHECR) hotspot reported recently by the Telescope Array (TA) and the warm spot by Pierre Auger Observatory. We describe the expected cosmic ray signal from a TDE and derive the constraints set by the time-scale for dispersion due to Galactic and intergalactic magnetic fields and the accretion time of the SMBH. We find that TDEs in M82 can explain the hotspot detected by the TA regardless of whether the UHECRs are composed of protons or heavier nuclei. We then check for consistency of the hot and warm spots from M82 and Cen A with the full-sky isotropic signal from all SMBHs within the Greisen-Zatsepin-Kuzmin (GZK) radius. This analysis applies to any scenario in which the hot/warm spots are real and due to M82 and Cen A, regardless of whether TDEs are the source of UHECRs. We find that the isotropic flux implied by the luminosity density inferred from M82 and Cen A is bigger than that observed by roughly an order of magnitude, but we provide several possible explanations, including the possibility of a local overdensity and the possibility of intermediate-mass nuclei in UHECRs, to resolve the tension.

Key words: acceleration of particles – accretion, accretion discs – black hole physics – galaxies: jets.

1 INTRODUCTION

In the past decade the ability to observe ultrahigh-energy cosmic rays[1] (UHECRs) has increased significantly with the advent of the Pierre Auger Observatory (PAO) and the Telescope Array (TA). Recently, both the TA and the PAO have detected regions of excess UHECRs as compared to an isotropic background (Abbasi et al. 2014; Aab et al. 2015), with statistical significances of $\gtrsim 3\sigma$ and $\gtrsim 2\sigma$, respectively.

The sources of UHECRs are still unknown. One possibility is active galactic nucleus (AGN) jets (Abraham et al. 2007). However, Farrar & Gruzinov (2009) derived a relation between the AGN electromagnetic luminosity and its UHECR luminosity. Zaw, Farrar & Greene (2009) then used the Veron-Cetty and Veron catalogue (Veron-Cetty & Veron 2010), along with this luminosity relation, to infer that the observed AGN are not luminous enough to explain the full-sky UHECR flux. Gamma-ray bursts (GRBs) are also capable of producing UHECRs (Waxman 1995), but they would have to have a rather flat spectrum of UHECRs produced by an individual GRB and would have to yield far more energy to UHECRs than to photons in order to explain the full-sky flux (Farrar & Gruzinov 2009).

We consider a third mechanism as the dominant source of UHECRs, namely tidal disruption events (TDEs). A star is disrupted by a super massive black hole (SMBH) when it passes by close enough that tidal forces overcome the binding energy of the star. Some fraction of the star then becomes bound to the SMBH and forms a short-lived accretion disc, which produces an intense flare,[2] while the rest continues on (Rees 1988). Some of the TDEs produce jets, which were first proposed as a source of UHECRs in Farrar & Gruzinov (2009) and then expanded upon in Farrar & Piran (2014), which showed that they can generate the luminosity required to account for the full-sky UHECR flux.

In 2014, the TA reported a ‘hotspot’ of UHECRs (Abbasi et al. 2014) in a circle of radius 20°, centred at a right ascension of $146\overset{\circ}{.}7$ and declination of $43\overset{\circ}{.}2$. He et al. (2016) tried to identify possible extragalactic sources for the hotspot, taking into account possible deflection of the UHECRs by Galactic and intergalactic magnetic fields (IGMFs). After accounting for random deflections by stochastic IGMFs, they drew a straight line through the images of the different rigidity bins of the events in the hotspot, expecting the source to lie along this line. Two possible sources were identified, M82 and Mrk 180. While Mrk 180 is located roughly 185 Mpc away, near the

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[1] For the purpose of this paper, UHECRs will be defined as cosmic rays with energies above 57 EeV.

[2] The SMBH does not need to be an AGN – i.e. actively accreting from the accretion disc – in order for the disruption to cause rapid accretion. The in-falling gas from the disrupted star could form an accretion disc with rapid accretion resulting in a relativistic jet outflow (Farrar & Gruzinov 2009).

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Greisen-Zatsepin-Kuzmin (GZK) radius, and is thus unlikely to be the source, M82 is a starburst galaxy only 3.8 Mpc away (Karachentsev & Kashibadze 2006) and moreover has an $\sim 3 \times 10^7$ $\mathrm{M}_\odot$ SMBH at its centre (Gaffney, Lester & Telesco 1993). The SMBH does not exhibit any AGN activity.

Likewise, the PAO has noted a ‘warm spot’, an excess of events in the direction of Centaurus A (Cen A). Cen A is also (coincidentally) approximately 3.8 Mpc away (Harris 2010), with an SMBH with a mass estimated to be 5×10^7 $\mathrm{M}_\odot$. Unlike M82’s, this SMBH does exhibit AGN activity.

In this paper, we investigate whether the TA hotspot can be explained by TDEs in M82. We first derive basic constraints to the model parameters from time-scale and energetic arguments. We surmise that the UHECR hotspot is in roughly steady state in which the UHECR flux results from several TDEs that have occurred within the time-scale for dispersion of a burst signal due to deflections in the Galactic and IGMFs (although we do briefly consider the possibility that the hotspot arises from a single burst). This hypothesis is consistent if UHECRs are composed of protons or heavier nuclei such as iron, although the consistent parameter space is a bit smaller for heavier nuclei. Similar arguments apply to the warm spot from Cen A. We then investigate whether the UHECR luminosity density implied by the observed fluxes from the SMBHs in M82 and Cen A is consistent with the isotropic UHECR intensity that is observed. We find that the isotropic flux inferred in this way is higher, by about a factor of 16, than the observed isotropic flux, but we point out several factors that might alleviate the apparent discrepancy.

The rest of this paper is organized as follows. In Section 2, we review briefly the evidence for the TA hotspot and the PAO warm spot and provide the fiducial values we use for the hotspot and warm-spot fluxes as well as the isotropic UHECR intensity. In Section 3, we discuss the constraints to TDE scenarios for the UHECR hot/warm spots that arise from energetics and time-scale considerations. In Section 4, we consider constraints to the scenario that arise from consistency of the hot/warm-spot fluxes with the isotropic UHECR intensity. In Section 5, we summarize, review the successes and weaknesses of the TDE explanation for the hot/warm spots and close with some speculations. In Section 6, we conclude by considering some possible future measurements.

2 THE HOT AND WARM SPOTS

The TA Collaboration reports evidence (Abbasi et al. 2014) for a UHECR excess in a circle of 20° radius. Because the TA does not report a value for the intensity in the hotspot, we use a value from Fang et al. (2014) who infer the (number) intensity J_{hs} in this hotspot to be

$$E^2 J_{\mathrm{hs}} = (4.4 \pm 1.0) \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}, \tag{1}$$

at an energy $E = 10^{19.5}$ eV. The hotspot energy flux in UHECRs with energies >57 EeV is $F_{\mathrm{hs}} = \Omega_{20^\circ} \int_{57\,\mathrm{EeV}}^{\infty} E\, J_{\mathrm{hs}}(E)\, \mathrm{d}E$, where $\Omega_{20^\circ} \simeq 0.38$ sr is the hotspot solid angle. The energy dependence of $J_{\mathrm{hs}}(E)$ at energies above 57 EeV is, however, quite uncertain in the hotspot, and even for the full-sky flux (see e.g. fig. 7 in Kistler, Stanev & Yüksel 2014, which shows considerable disagreement between PAO and TA at the highest energies), so we use $\int_{57\,\mathrm{EeV}}^{\infty} E\, J_{\mathrm{hs}}(E)\, \mathrm{d}E = E^2\, J_{\mathrm{hs}}|_{E=57\,\mathrm{EeV}}$. We therefore take the energy flux in the hotspot to be

$$F_{\mathrm{hs}} = 1.7 \times 10^{-8}\, F_{1.7}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}, \tag{2}$$

and keep the quantity $F_{1.7}$, which parametrizes our uncertainty in the flux, in our expressions below.

Likewise, we take the observed isotropic (energy) intensity above 57 EeV to be $I_{\mathrm{o}} = 7.9 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}. We take this value from Kistler et al. (2014), which uses data from Aab et al. (2013) and Abu-Zayyad et al. (2013). Again, to be consistent with our treatment of the hotspot flux, we take this to be the value of $E^2 J_{\mathrm{iso}}$ at $E = 57$ EeV. This isotropic flux appears below only in comparison to the hotspot flux, and so it is appropriate to treat the full-sky flux in the same way as the hotspot flux.

We estimate the UHECR energy flux from Cen A implied by the PAO warm spot as follows: Abreu et al. (2010) finds 13 events within a circle of radius 18°, where 3.2 are expected from an isotropic distribution. We thus take the energy flux from Cen A to be $(13 - 3.2)/3.2 \approx 3$ times the isotropic energy flux in that circle, or

$$F_{\mathrm{ws}} = 7.6 \times 10^{-9}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}, \tag{3}$$

keeping in mind the considerable uncertainty in this value.

3 TIME-SCALES AND ENERGETICS

Our aim here is to understand whether TDEs from accretion of stars on to the SMBH in M82 may be responsible for the UHECR hotspot. We begin with some basic considerations, starting with time-scales.

The hotspot is observed to be spread over an angular region of size $\theta \sim 20^\circ$. Such a spread is to be expected due to scattering in turbulent IGMFs as the UHECRs propagate the 3.8 Mpc distance from M82, and there may be additional scattering (particularly for iron nuclei) from magnetic fields in the Milky Way. The rms deflection angle for a UHECR of charge Z in a homogeneous turbulent magnetic field in the limit of small deflections per coherence length is (Waxman & Miralda-Escude 1996)

$$\delta_{\mathrm{rms}} \approx 3\overset{\circ}{.}6\, Z E_{20}^{-1} r_{100}^{1/2} \lambda_{\mathrm{Mpc}}^{1/2} B_{\mathrm{nG,rms}}, \tag{4}$$

where $B_{\mathrm{nG,rms}}$ is the rms strength of the magnetic field in nG, E_{20} is the UHECR energy in units of 10^{20} eV, $r_{100} = r/100$ Mpc is the distance over which the magnetic fields act, and λ_{Mpc} is the magnetic-field coherence length in units of Mpc. We take $\delta_{\mathrm{rms}} = \theta/2$ so that a two-dimensional region of size θ encloses ~86 per cent of the events. Consider first scattering in Galactic magnetic fields. Characteristic values might then be $\lambda_{\mathrm{Mpc}} \sim 10^{-4}$, $r_{100} \sim 10^{-4}$ and $B_{\mathrm{nG}} \sim 10^3$ (Beck et al. 2016), implying Galactic deflection angles $\delta_{\mathrm{rms,\,GMF}} \sim 0\overset{\circ}{.}36 Z$. We thus infer, for these values, that for iron nuclei all the scattering could conceivably arise from Galactic magnetic fields, although for protons, the scattering must arise in the IGMF. The value of λ_{Mpc} within the Milky Way is, however, not fully agreed upon yet (Beck et al. 2016). A value of λ_{Mpc} slightly larger than 10^{-4} would still give a $\delta_{\mathrm{rms}} \sim 10^\circ$ for iron nuclei, but a smaller value would require the scatter of iron nuclei in the IGMF to be comparable to or greater than the scatter in the GMF. Although we have surmised that UHECRs are dispersed by turbulent magnetic fields, there could also be some additional dispersion due to coherent fields (Farrar 2014) in the Galaxy, a possibility we explore further in Pfeffer et al. (in preparation).

Either way, scattering in magnetic fields also gives rise to a spread (Waxman 1995; Farrar & Piran 2014)

$$\tau \simeq 3 \times 10^5 \left(\frac{r_{100} B_{\mathrm{nG}}}{E_{20}}\right)^2 \lambda_{\mathrm{Mpc}} Z^2\,\mathrm{yr}$$
$$\simeq 3.5 \times 10^5 \left(\frac{\delta_{\mathrm{rms}}}{3\overset{\circ}{.}6}\right)^2 r_{100}\,\mathrm{yr}, \tag{5}$$

in the arrival times for UHECRs from a single TDE. Thus, if all the scattering takes place in the Milky Way, for which $r_{100} \sim 10^{-4}$, then

$\delta_{\rm rms} \sim 10^\circ$ implies a dispersion of $\tau \sim 270$ yr in the UHECR arrival times. If scattering occurs primarily in IGMFs, then the spread in arrival times is $\tau \sim 10^5$. This is also roughly the same value of τ for iron nuclei if they are scattered a comparable amount in the IGMF and GMF. We thus infer that UHECRs are spread in arrival time by some magnetic-dispersion time-scale $270\,{\rm yr} \lesssim \tau \lesssim 10^5$ yr, with protons and iron nuclei at the higher end for a strong IGMF and iron nuclei at the lower end only if there is an extremely weak IGMF ($B_{\rm nG} \approx 10^{-3}$ nG).

We now consider energetics. If the observed flux of UHECRs in the hotspot is $F_{\rm hs} \simeq 1.7 \times 10^{-8} F_{1.7}$ GeV cm^{-2} sec^{-1}, then the implied isotropic-equivalent source luminosity is $L = 4\pi D^2 F \simeq 8.3 \times 10^{-7}\, F_{1.7}\, {\rm M}_\odot c^2\ {\rm yr}^{-1}$ (where $D = 3.8$ Mpc is the distance). If the observed UHECRs are due to a single TDE spread over a time τ, then the isotropic-equivalent energy implied with $\tau \simeq 270$ yr, the minimum τ possibly allowed for iron nuclei, is $2.2 \times 10^{-4}\, F_{1.7}\, {\rm M}_\odot c^2$. If the dispersion time is $\tau \simeq 10^5$ yr, the value required for protons, then the isotropic-equivalent energy is $8.3 \times 10^{-2}\, F_{1.7}\, {\rm M}_\odot c^2$. Of course, if the TDE is beamed into a solid angle that subtends a fraction $\Omega_{\rm jet} \sim 0.1$ of 4π, then the energy requirements can be relaxed by a factor of ~10. Still, we conclude that if UHECRs are iron nuclei, the hotspot is conceivably due to a single burst. If the UHECRs are protons, the energetics are prohibitive, unless the Milky Way magnetic-field parameters are altered so that the angular spread in the hotspot arises from scattering in the Milky Way. Even if the energetics can somehow be worked out, the notion that we are seeing a hotspot just from M82 because of some chance occurrence (an extraordinarily energetic TDE at just the right time) is unsatisfying, and even more unsatisfying if we must also explain the warm spot as some similar chance occurrence in Cen A.

Another possibility is that the observed hotspot arises not from a single TDE, but from a number of TDEs in M82. This may occur if the dispersion τ in arrival times exceeds the typical time Δt between TDEs in M82. If so, then we are seeing UHECRs from $N \simeq (\tau/\Delta t) \gtrsim 1$ bursts at any given time. The hotspot flux in this case will vary by a fractional amount $\sim N^{-1/2}$ over time-scales $\sim\tau$. However, over the ~5-yr observation, the observed flux will remain effectively constant. This scenario, as we will now show, is plausible.

We suppose that stars (which we assume for simplicity to all have a mass ${\rm M}_\odot$) are captured by the SMBH with a rate Γ. We then suppose that only a fraction ζ produce the type of jets that can accelerate UHECRs and that a fraction ξ of the stellar rest-mass energy ${\rm M}_\odot c^2$ goes into UHECRs. We further suppose that the UHECR emission may be beamed into a fraction $\Omega_{\rm jet}$ of the 4π solid angle of the sphere. In order to obtain the observed UHECR hotspot flux in steady state, we require that stars be captured by the SMBH at a rate

$$\Gamma = 8.3 \times 10^{-7} \left(\frac{\Omega_{\rm jet} F_{1.7}}{\xi \zeta} \right) {\rm yr}^{-1}. \tag{6}$$

The mean time between UHECR-producing events is

$$\Delta t = (\zeta \Gamma)^{-1} = 1.26 \times 10^6\, \frac{\xi}{\Omega_{\rm jet} F_{1.7}}\ {\rm yr}. \tag{7}$$

Both equations (6) and (7) are for a single SMBH with jets produced by TDEs pointed at the Earth. Here we assume that all of the jets produced by TDEs from a particular SMBH will always point in the same direction. If we were to assume that the direction of these jets were uncorrelated with each other, then an extra factor of $\Omega_{\rm jet}$ would need to be added to equations (6) and (7). The new factor of $\Omega_{\rm jet}$ would cancel out with the previous because only $\Omega_{\rm jet}$ percentage of jets would be beamed towards the Earth. If this mean time is to be smaller than the magnetic-dispersion time τ, we require

$$\frac{\xi}{\Omega_{\rm jet} F_{1.7}} \lesssim 7.7 \times 10^{-2}\, \tau_5, \tag{8}$$

where τ_5 is the magnetic-dispersion time in units of 10^5 yr.

We now compare the mass-accretion rate implied by equation (6) with the Eddington rate $\dot{M} = L_{\rm Edd}/c^2 \simeq 3.8 \times 10^{45}\, M_3\, {\rm erg\, s^{-1}} c^{-2}$, where M_3 is the SMBH mass in units of $3 \times 10^7\, {\rm M}_\odot$, for M82. Assuming that half of the disrupted star's mass is accreted, we find that the mass-accretion rate is smaller than Eddington if

$$\frac{\xi}{\Omega_{\rm jet} F_{1.7}} \gtrsim 6.0 \times 10^{-6} M_3^{-1} \zeta^{-1}. \tag{9}$$

It is not, strictly speaking, required that this condition be respected. It is conceivable that an SMBH could appear quiescent, even with a super-Eddington time-averaged mass-accretion rate, if the accretion is episodic. Still, the scenario may be a bit more palatable if we do not have to wave away a super-Eddington accretion rate in this way. Or put it another way, it is simply interesting to note that the scenario can work with a sub-Eddington time-averaged accretion rate as long as equations (8) and (9) are satisfied, or as long as

$$\zeta \gtrsim \frac{7.6 \times 10^{-5}}{\tau_5 M_3}. \tag{10}$$

This quantity must be $\zeta \leq 1$, and is estimated to be $\zeta \sim 0.1$ (Farrar & Piran 2014, although that is a value for the average over all SMBHs, and does not necessarily apply to a single SMBH). Such a value is easily accommodated if $\tau_5 \sim 1$, as we might expect for UHECR protons, and even fits for iron nuclei, for which the lowest possible magnetic dispersion time gives $\tau_5 \sim 2.7 \times 10^{-3}$.

We have thus shown that the TA hotspot can be explained as a roughly steady-state phenomenon by the sub-Eddington capture and tidal disruption of stars by the SMBH in M82. The scenario works independent of whether the UHECRs are protons or iron nuclei, although the time-scale parameter space is a bit narrower for iron nuclei, a consequence of the larger deflection of iron nuclei in the Milky Way magnetic field.

4 ISOTROPIC FLUX

We now investigate whether the isotropic UHECR flux implied by this scenario is consistent with that observed under the assumption that the UHECR luminosity of M82 and of Cen A are fairly typical for such SMBHs. This analysis applies not only to the hypothesis that TDEs are responsible for the hot and warm spots, but to any scenario in which there are hot/warm spots associated with Cen A and M82.

We begin with a simple analysis. The isotropic-equivalent luminosities of M82 and Cen A are, respectively, $2.9 \times 10^{43}\, F_{1.7}$ GeV s^{-1} and $1.4 \times 10^{43}\, F_{1.7}$ GeV s^{-1}. Both SMBHs are at a distance $R \lesssim 4$ Mpc, and so the UHECR luminosity density in a 4-Mpc sphere around us is $\rho_{\rm L} \simeq 5.4 \times 10^{-33} F_{1.7}$ GeV cm^{-3} s^{-1}. If the UHECR emissions from Cen A and M82 are both beamed into a fraction $\Omega_{\rm jet}$ of the 4π solid angle, then $\rho_{\rm L}$ is reduced by $\Omega_{\rm jet}$. If M82 and Cen A are not atypical, though, then there must be $\sim\Omega_{\rm jet}^{-1}$ other beamed UHECR sources, aimed in other directions, for every source that we see. This then cancels the $\Omega_{\rm jet}$ beaming reduction leaving $\rho_{\rm L}$ unchanged. Since both Cen A and M82 appear, in the jetted-TDE scenario, to be aimed at us, we infer that $\Omega_{\rm jet}$ is unlikely to be small in this scenario. The tension we will find below between the hot/warm-spot fluxes and the isotropic intensity can be relaxed, though, if both Cen A and M82 just happen to be highly beamed and both in our direction. If our local neighbourhood is not atypical, then $\rho_{\rm L}$ provides an estimate of the universal UHECR luminosity density. If the local density is greater by a factor f_ρ than the cosmic mean density, then the universal UHECR luminosity density is $\rho_{\rm L}/f_\rho$.

The isotropic UHECR intensity (energy per unit area per unit time per unit solid angle) is

$$I = \int_0^{R_G} {\rm d}r\, r^2\, f(r) \frac{\rho_{\rm L}}{4\pi r^2} = \frac{\rho_{\rm L}}{4\pi} \int_0^{R_G} {\rm d}r\, f(r) = \frac{\rho_{\rm L} R_G}{8\pi}, \qquad (11)$$

where $R_G \simeq 200$ Mpc is the GZK radius, and the second equality is obtained by approximating the fraction of UHECR energy emitted at a distance r that makes it to us to be $f(r) \simeq 1 - (r/R_G)$ (Kotera & Olinto 2011). If the TA hotspot and PAO warm spot are real and attributed to M82 and Cen A, respectively, then the isotropic UHECR flux should be $I = 1.37 \times 10^{-7}\, F_{1.7}\, f_\rho^{-1}$ GeV cm^{-2} s^{-1} sr^{-1}. This is, for $f_\rho = 1$, 16 times greater than the isotropic intensity $I_{\rm o} = 7.9 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}. The discrepancy cannot be alleviated with a smaller value of $F_{1.7}$ because, as discussed after equation (2), we are using the specific intensities at $E \simeq 10^{19.5}$ eV, which are fairly well determined, as proxies for the full energy flux and isotropic intensity.

It is, however, likely that the tension can be alleviated, at least in part, with a value $f_\rho > 1$. The local overdensity is uncertain, but as one indication of the value of f_ρ, we can use the total SMBH mass in the $R \simeq$ Mpc sphere, assuming that the UHECR luminosity density is proportional to the density of mass SMBHs. In addition to the SMBHs in Cen A and M82, there is also the $\sim 4 \times 10^6\, {\rm M}_\odot$ SMBH in the Milky Way and the $\sim 10^8\, {\rm M}_\odot$ SMBH in Andromeda, a $\sim 7.7 \times 10^7\, {\rm M}_\odot$ SMBH in M81, as well as a $\sim 10^6\, {\rm M}_\odot$ SMBH in M32. This totals to $\sim 2.5 \times 10^8\, {\rm M}_\odot$ in SMBHs within a distance $R \simeq 4$ Mpc implying a local SMBH density $\simeq 9.3 \times 10^5\, {\rm M}_\odot$ Mpc^{-3}, roughly three times the universal SMBH density $\simeq 2.9 \times 10^5\, {\rm M}_\odot$ Mpc^{-3} (Dzanovic et al. 2007). There is still residual factor of ~ 5 discrepancy that remains, even accounting for this $f_\rho \sim 3$, that must be accounted for if the TDE explanation for the TA and PAO hotspots is to remain viable. This level of discrepancy is we believe, given the order-of-magnitude nature of the analysis, as well as the measurement and astrophysical uncertainties, not necessarily fatal for the TDE scenario. The local luminosity density $\rho_{\rm L}$ we inferred could have been reduced a bit by considering a sphere of slightly larger radius; there are uncertainties almost of the order of unity in the measured fluxes; and the Poisson fluctuation in our inference of $\rho_{\rm L}$ is also of the order of unity.

So far we have been using the UHECR flux from M82 and Cen A to infer a luminosity density, and the uncertainty from small-number statistics has been noted above. There is, however, an additional uncertainty that may arise from the dependence of the mean TDE rate on SMBH mass. SMBHs are distributed with a mass function ${\rm d}n/{\rm d}M$ (Dzanovic et al. 2007; Caramete & Biermann 2010), and there is evidence that the TDE rate varies with the SMBH mass. We infer an UHECR luminosity density from measurement of the UHECR flux from one or two $\sim 3 \times 10^7$ SMBHs. Suppose, though, that the TDE rate varies as $\Gamma(M) = \Gamma(M = 3 \times 10^7\, {\rm M}_\odot)(M/3 \times 10^7\, {\rm M}_\odot)^{-\beta}$, the luminosity density we infer from the measured M82 flux would then be $L_{\rm tde} \int ({\rm d}n/{\rm d}M)(M/3 \times 10^7\, {\rm M}_\odot)^{-\beta}$, where $L_{\rm tde}$ is the UHECR luminosity from one burst. If we then use the best estimate $\beta \simeq 0.22$ from Stone & Metzger (2016), the SMBH mass function from Dzanovic et al. (2007), and integrate from 10^5 (below which there is little evidence for SMBHs) to $10^8\, {\rm M}_\odot$ (above which stars will be swallowed without being tidally disrupted; Magorrian & Tremaine 1999), we find – unfortunately for the TDE scenario – a luminosity density ~ 1.7 times higher. This power-law index β is, however, quite uncertain, and if we suppose that it is instead $\beta \simeq 0.5$, then the inferred luminosity density is decreased by ~ 0.5. This may thus provide some wiggle room for the tension between the M82 and Cen A fluxes and the isotropic intensity, although is unlikely to be the entire explanation. Changes to the upper and lower limits of integration do not alter this conclusion. We do note that the masses of the SMBHs in Cen A and M82 are quite similar, both around $(3 - 5) \times 10^7\, {\rm M}_\odot$. If, for some reason, the TDE rate were to be maximized for SMBHs of this mass, and smaller for SMBHs of both lower and higher masses, then the universal UHECR luminosity could be reduced significantly relative to what we inferred above. In this case, the high fluxes towards M82 and Cen, relative to the isotropic intensity, would be a consequence of our chance proximity to two SMBHs of this specific mass.

The tension between the hot/warm-spot fluxes and the isotropic intensity may also be relaxed if UHECR consists at the source, at least in part, of other nuclei, like helium, carbon, nitrogen or oxygen. The path length of such nuclei through the intergalactic medium is far smaller than the ~ 200 Mpc GZK distance of protons and iron nuclei (Kotera & Olinto 2011). If there is significant UHECR production in such nuclei, then the isotropic intensity inferred from the measured $D \lesssim 4$ Mpc luminosity density will be smaller. Such a scenario implies a different observed UHECR composition in the hot/warm spots and in the isotropic component. There may already be some evidence for intermediate-mass nuclei in UHECRs Aab et al. (2014).

5 DISCUSSION: TDE SCORECARD

The previous sections lead to the following conclusion: Energetics make it unlikely, although not impossible, that the hotspot towards M82 is the result of a single burst, a tension that is probably greater if UHECRs are protons rather than iron nuclei. Dispersion in Galactic and IGMFs disperse the UHECR arrival times. This magnetic-dispersion time, if anything, has to be higher for protons than for iron nuclei. The single-burst scenario is also unappealing as it implies that the hotspot is evanescent, something that we see as a chance occurrence. This chance event is made even less likely if the warm spot towards Cen A is also explained another chance event.

The energetics requirements are relaxed, though, if the UHECRs in the hotspot result from a number of TDEs in M82 that have occurred over a magnetic dispersion time, a scenario in which the UHECR fluxes in the hot/warm spots are roughly in steady state. The required efficiency of UHECR production in each TDE event can then be reduced at the expense of an increased TDE rate. We do show, though, that the TDE rates can still remain low enough so that the time-averaged accretion rate in M82 remains sub-Eddington, something that may be desirable, though not necessarily required, to explain the quiescent nature of the SMBH in M82. (This is less of a concern, of course, for Cen A, which is quite active.) This latter, softer, requirement, is satisfied, though, only at the expense of introducing a slight tension in the required UHECR efficiency per TDE. That tension can be reduced if the TDE is highly beamed. Significant beaming introduces, however, the notion that the UHECR flux from M82 results from our chance position within the TDE's jet, an ingredient that is less appealing if we must also explain the PAO warm spot in terms of TDEs from Cen A's SMBH. Any significant beaming requirement for Cen A would also be more difficult given that the radio observed jet in Cen A is not pointed towards us.

We note that the time between jetted TDEs in our scenario is a bit higher than the rate expected from existing TDE statistics. Scalings between TDE rates and SMBH masses derived in Stone & Metzger (2016) suggest that the characteristic time between TDEs in a $3 \times 10^7\,\mathrm{M}_\odot$ SMBH is $\Gamma^{-1} \sim 10^4$ yr. Farrar & Piran (2014) estimate further that only a fraction $\zeta \sim 0.1$ of TDEs are jetted. If we take this value for M82, then the time between UHECR-producing events is roughly the same as the magnetic-dispersion time. There are, however, considerable uncertainties in these estimates, and there may also be considerable variation between the jetted fraction for one particular SMBH and the mean inferred by averaging over all SMBHs.

We then investigated the isotropic flux of UHECRs that is expected if the sources of UHECRs in M82 and Cen A are not atypical. This analysis applies not only to the hypothesis that the UHECR sources in M82 and Cen A are TDEs, but to any scenario in which there are hot/warm spots from Cen A and M82. The observed UHECR fluxes from M82 and Cen A imply a local UHECR luminosity density. We find that if the universal UHECR luminosity density is taken to be this local luminosity density, then the isotropic UHECR intensity is about 16 times larger than that observed. There is, however, some evidence that the local mass density in SMBHs is higher, perhaps by ∼3, than the universal density. Even so, there is still a tension, at the ∼5 level, between the hot/warm spot fluxes and the isotropic intensity. Possible explanations for this residual tension may arise from our underestimate of the local overdensity; small-number statistics in the number of SMBHs; uncertainties in the characterization of the hot/warm spots; a mixed composition of UHECRs including intermediate-mass nuclei with smaller GZK cut-offs; and/or some SMBH-mass dependence of the TDE rate.

Before closing, it is interesting to wonder whether the SMBH $\sim 4 \times 10^6\,\mathrm{M}_\odot$ SMBH at the centre of Milky Way (Ghez et al. 2008) should produce UHECRs. The answer is probably not. Assuming the Milky Way is a core galaxy, the expected time, from Stone & Metzger (2016), between TDEs for the Milky Way's SMBH is 3.9×10^4 yr. As discussed above, the magnetic-dispersion time within the Milky Way can be, for reasonable magnetic-field parameters, quite a bit smaller than this. It is thus not surprising that we do not see a UHECR hotspot towards the Galactic Centre, even if our SMBH does produce TDEs at the expected rate.

Finally, we speculate on the possibility that the IMBH in M82 (Patruno et al. 2006; Pasham, Strohmayer & Mushotzky 2014, should the evidence for that IMBH survive) may have something to do with the TA hotspot. It may be possible for IMBHs to produce their own TDEs. Another possibility is that IMBHs might perturb the orbits of stars in a way similar to the Kozai mechanism (Perets, Hopman & Alexander 2007), and thus increase the rate of TDEs in the host galaxy. The difference in the UHECR flux from M82 and Cen A might thus be explained by an IMBH-enhanced TDE rate in M82 relative to what it would be otherwise.

6 CONCLUSIONS

We have investigated the possibility that TDEs fuelled by the accretion of stars on to the SMBH in M82 could account for the hotspot reported by the TA and that TDEs on to the SMBH in Cen A could explain the warm spot seen by the PAO towards Cen A. Given the measurement uncertainties and considerable astrophysical uncertainties, it is difficult to make precise statements about the viability of the scenario. Although there are some tensions at the order-of-magnitude level, outlined in detail above, there is, as far as we can tell, no silver bullet that rules the scenario out at the level of more than an order of magnitude.

Future measurements should help shed additional light on the viability of TDEs as the sources of UHECRs. The viability of the TDE scenario for the isotropic flux has been discussed in Farrar & Gruzinov (2009) and Farrar & Piran (2014), but if the hot/warm spots are real and attributed to M82 and Cen A, then there are additional challenges discussed above. It will be interesting to see if the evidence for the hot and warm spots continues with more data (or perhaps gains additional support from independent measurements, such as ultrahigh-energy-neutrino detection). If so, the characterization of those fluxes should improve. For example, there may be differences, which we will explore elsewhere (Pfeffer et al., in preparation), in the energy distribution of UHECRs in the hot/warm spots, which come from 3.8 Mpc, versus those in the rest of the sky, which come from much greater distances and thus experience greater photopion absorption.

ACKNOWLEDGEMENTS

The authors would like to thank Julian Krolik, Joe Silk, Meng Su and Ilias Cholis for useful discussions. We especially thank Glennys Farrar for valuable detailed comments on an earlier draft. This work was supported by NSF Grant No. 0244990, NASA NNX15AB18G, the John Templeton Foundation and the Simons Foundation.

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