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ULTRA-HIGH-ENERGY COSMIC RAYS FROM CENTAURUS A: JET INTERACTION WITH GASEOUS SHELLS

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ABSTRACT

Ultra-high-energy cosmic rays (UHECRs), with energies above $\sim 6 \times 10^{19}$ eV, seem to show a weak correlation with the distribution of matter relatively near to us in the universe. It has earlier been proposed that UHECRs could be accelerated in either the nucleus or the outer lobes of the nearby radio galaxy Cen A. We show that UHECR production at a spatially intermediate location about 15 kpc northeast from the nucleus, where the jet emerging from the nucleus is observed to strike a large star-forming shell of gas, is a plausible alternative. A relativistic jet is capable of accelerating lower energy heavy seed cosmic rays (CRs) to UHECRs on timescales comparable to the time it takes the jet to pierce the large gaseous cloud. In this model, many CRs arising from a starburst, with a composition enhanced in heavy elements near the knee region around PeV, are boosted to ultra-high energies by the relativistic shock of a newly oriented jet. This model matches the overall spectrum shown by the Auger data and also makes a prediction for the chemical composition as a function of particle energy. We thus predict an observable anisotropy in the composition at high energy in the sense that lighter nuclei should preferentially be seen toward the general direction of Cen A. Taking into consideration the magnetic field models for the Galactic disk and a Galactic magnetic wind, this scenario may resolve the discrepancy between HiRes and Auger results concerning the chemical composition of UHECRs.

Key words: acceleration of particles – galaxies: individual (Cen A) – galaxies: ISM – galaxies: jets – radio continuum: galaxies

Online-only material: color figure

1. INTRODUCTION

To understand the origin of cosmic rays (CRs), it is important to distinguish between the lower energy CRs which can be contained within the magnetic field of our Galaxy and thus have energies of up to about 3×10^{18} eV for heavy nuclei and those that are even more energetic. The bulk of the CRs below that energy can be explained by supernova explosions, while the extremely energetic ones probably originate from either some class of active galactic nuclei (Ginzburg & Syrovatskii 1964; Biermann & Strittmatter 1987) or some extreme type of stellar activity such as gamma-ray bursts (Waxman 1995). Indeed, the spectrum of CRs shows a kink near 3×10^{18} eV, matching the expectation that their origin changes around this energy threshold.

Stellar explosions can account for the flux, spectrum, particle energy, and chemical composition of the less energetic CRs, considering that all very massive stars explode into their pre-existing winds (e.g., Prantzos 1984; Stanev et al. 1993; Meyer et al. 1997). Further quantitative confirmation of this picture has now emerged from detailed observations of CR electrons and positrons, as well as the *Wilkinson Microwave Anisotropy Probe* haze (Biermann et al. 2009b, 2010). The supernova origin of Galactic CRs may lead us to an understanding of the seed particle population (Biermann et al. 2009a) on which active galactic nuclei energizing radio galaxies can operate their acceleration processes.

The origin of ultra-high-energy cosmic rays (UHECRs) is still an unresolved issue, but a few clues have begun to emerge. Although their arrival directions are nearly isotropic, a general correlation with the distribution of matter has been noted by the Auger observatory (Stanev et al. 1995; Auger Collaboration 2008a, 2008b); although it is disputed by the High Resolution Fly's Eye cosmic-ray detector (HiRes) observatory (Abbasi et al. 2008, 2010a). In particular, there may be excess events with arrival directions close to the nearby radio galaxy Centaurus A (Auger Collaboration 2008a; Abraham et al. 2009). There are contradicting claims from experiments as to whether the UHECR events are heavy nuclei (Auger; Abraham et al. 2010) or purely protons (HiRes; Abbasi et al. 2010b). Both possibilities need to be explored.

In a picture where UHECR energies are attained by a single kick up from a seed population (Gallant & Achterberg 1999) through the action of a relativistic jet, these events can indeed involve heavy nuclei (Biermann et al. 2009a). In such a scheme, the seed particles are the CRs near the spectral knee (Stanev et al. 1993) and the relativistic shock is very likely to arise from a jet carving out a new channel after being launched from a primary central black hole that has been reoriented following the merger of the nuclear black holes of two merging galaxies (Gergely & Biermann 2009). In this scenario, all the UHECR particles are a mix of heavy nuclei, and the spectrum in Stanev et al. (1993) actually gives an adequate fit to the Auger data (Biermann et al. 2009a). See Figure 1. The sky distribution is easily isotropized by the intergalactic magnetic fields (Das et al. 2008);

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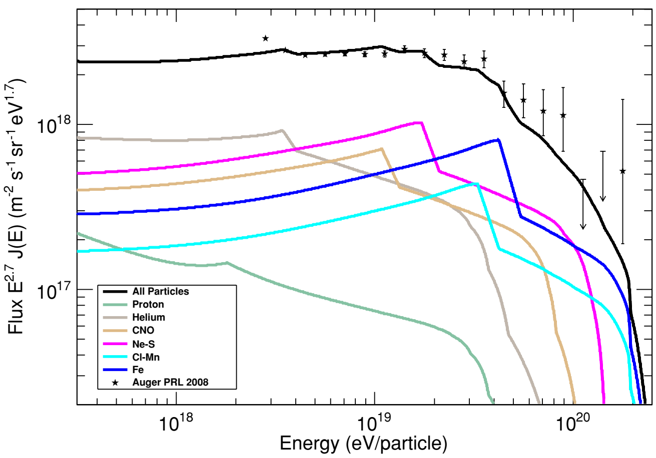

Figure 1. Testing the shift of the spectrum in the paper of Stanev et al. (1993) with Auger data, using the propagation calculations of Allard et al. (2008) with a 3.8 Mpc distance to Cen A and assuming all isotropizing is in the magnetic wind of our Galaxy (Everett et al. 2008). Note that the break here is due to the MHD structure of massive star winds, pushed to EeV energies by a highly relativistic shock.

(A color version of this figure is available in the online journal.)

for the case of heavy nuclei, one is even confronted with the possibility of excessive scattering (Biermann et al. 2009a). This picture also allows the incorporation of the Poynting flux limit (Lovelace 1976): the particles to be accelerated must remain confined within the jet diameter. This condition translates into a lower limit for the jet power, allowing most UHECR particles to originate from the jet interacting with lower energy CRs produced in the starburst in the central region of Cen A.

Therefore, we explore a scenario based on the observed head-on encounter of the Cen A jet with magnetized interstellar clouds (Gopal-Krishna & Saripalli 1984; Kraft et al. 2009; Gopal-Krishna & Wiita 2010) from which UHECR acceleration ensues. A distinctly appealing aspect of this proposal is that the postulated jet–cloud interaction is actually observed within the northern lobe of Cen A, whereby the jet is seen to be disturbed, bent westward, and possibly disrupted temporarily (Morganti et al. 1999; Oosterloo & Morganti 2005). Since any supersonic flow reacts to a disturbance with shock formation, this in turn could cause particle acceleration. Note that the *Fermi*/Large Area Telescope error circle for the peak of the gamma-ray emission (Abdo et al. 2010) encompasses the jet–cloud interaction region, at the base of the northern middle lobe of Cen A, about 15 kpc from the nucleus.

2. ACCELERATION IN CEN A FROM A JET INTERACTING WITH GASEOUS SHELLS

The key point is that the interaction of the northern jet with a gaseous shell in the northern middle lobe has clearly been seen (Oosterloo & Morganti 2005; Kraft et al. 2009), and massive star formation is revealed at the location of the interaction by the *Galaxy Evolution Explorer* UV image (Kraft et al. 2009). Although other mechanisms can bend and disrupt radio jets, only a jet–shell interaction can explain the variety of data (radio, H I, UV, X-rays) for Cen A (Kraft et al. 2009). It has also been argued that the oft-debated peculiar morphology of the northern middle radio lobe can be readily understood in terms of the same jet–shell collision (Gopal-Krishna & Wiita 2010).

An important aspect of the basic acceleration physics to be stressed is that when particles are accelerated in a shock propagating parallel to the magnetic field lines, the maximum particle energy $E_{\rm max}$ is given by Hillas (1984), Ginzburg & Syrovatskii (1964), and Stanev (2004): $E_{\rm max} = e\,Z\,\beta_{\rm sh}\,R_B\,B$, where e is the elementary electric charge, Z is the numerical charge of the particle, $\beta_{\rm sh}$ is the shock speed in units of the speed of light, the available length scale is R_B, and the strength of the magnetic field is B. However, when the shock propagation is highly oblique, the corresponding limit (Jokipii 1987; Meli & Biermann 2006) becomes

$$E_{\rm max} = e\,Z\,R_B\,B, \tag{1}$$

which is independent of the shock velocity. Invoking relativistic shocks obviously adds an additional factor of $\gamma_{\rm sh}$, the shock's Lorentz factor (Gallant & Achterberg 1999). Losses will curtail this maximum attainable energy (Hillas 1984; Biermann & Strittmatter 1987).

We now focus on the particle acceleration due to the observed interaction of the jet with shells of fairly dense gas. Cen A has long been known to have a number of stellar shells, located in the vicinity of both the northern and southern lobes (Malin et al. 1983). Some of these shells have later been found to contain large amounts of dense atomic (Schiminovich et al. 1994) and even molecular (Charmandaris et al. 2000) gas ($\sim 7.5\times10^8\,M_\odot$). These shells are generally thought to have originated from the merger of a massive elliptical with a disk galaxy (Quinn 1984), very probably the same merger that gave rise to the peculiar overall appearance of this large elliptical galaxy marked by a striking dust lane. Radio maps reveal that the northern jet has encountered such shells at distances of 3.5 and 15 kpc from the core, and flared up each time to the same side, thereby forming the northern inner and the northern middle lobes (Gopal-Krishna & Saripalli 1984; Gopal-Krishna & Wiita 2010). Simulations of such collisions indicate the formation of strong shocks where the jets impinge upon gas clouds (e.g., Choi et al. 2007).

We must ask whether the maximum observed particle energies, of order 10^{21} eV, are actually attainable in such interactions. Accelerating particles to such copious energies requires that the Larmor motion of a particle must fit within the gaseous cloud, both before and after the shock that forms inside the cloud by interaction with the impinging relativistic jet. This leads to the condition $E_{\rm max} \lesssim e\,Z\,B_{cl}\,R_{cl}$, also called the Hillas limit (Hillas 1984), which is a general requirement to produce UHECR via shocks.

Adopting the very reasonable parameter values of 3 kpc for R_{cl}, the approximate observed size of the H I shell found in the northern middle lobe of Cen A (Oosterloo & Morganti 2005; Gopal-Krishna & Wiita 2010), and 3×10^{-6} G for the magnetic field, it follows that the energy must remain below $Z\times10^{19}$eV. Since particles are observed up to about 3×10^{20} eV (Bird et al. 1994), this implies that heavy nuclei, such as Fe, are much preferred for this mechanism to suffice; however, if a stronger magnetic field were present, this would ease the requirement on the abundances and allow for CRs to be accelerated to even higher energies. The magnetic field in the shell is not well constrained, but the required value is modest.

The Hillas limit condition (Hillas 1984) mentioned above can be expressed another way (Lovelace 1976). Taking the energy needed for particle acceleration to derive from a jet, we can connect the time-averaged energy flow along the jet with the condition that the accelerated particles are contained within the jet diameter,

$$L_{\rm jet} \gtrsim 10^{47}\,{\rm erg\,s^{-1}}\,f_{\rm int}\left(\frac{E_{\rm max}}{Z\times10^{21}\,{\rm eV}}\right)^2, \tag{2}$$

where $f_{\rm int}$ is an intermittency factor describing the temporal fluctuations of the energy outflow. Equality in this critical expression would imply that the energy flow in the jet is an entirely electromagnetic Poynting flux, an unrealistic extreme scenario. For Cen A we require both an intermittency factor <1 and presumably also heavy nuclei, e.g., $Z \simeq 26$. We find $f_{\rm int} \lesssim 0.75$ in order to match the kinetic jet power, which has been argued to be $L_{\rm jet} \simeq 10^{43}$ erg s^{-1} through several different approaches (Whysong & Antonucci 2003; Abdo et al. 2010; Kraft et al. 2009, and references therein). The recent HESS observations of Cen A (Aharonian et al. 2009) detected an ultra-high energy ($>$250 GeV) photon luminosity of only $\simeq 2.6 \times 10^{39}$ erg s^{-1}, but the entire photon luminosity in gamma rays ($>$100 keV) is $\sim 2 \times 10^{42}$ erg s^{-1}, and thus also consistent with $L_{\rm jet} \simeq 10^{43}$ erg s^{-1}.

We next examine whether the inferred luminosity of UHECRs is indeed attainable. Assuming the observed spectrum of the jet corresponds to a CR particle spectrum of about $E^{-2.2}$ leads to the requirement that the observed power in UHECR particles must be multiplied by a factor of about 200 in order to integrate over the power-law spectrum. The data then require a luminosity of about 10^{42} erg s^{-1}, still below the inferred jet power of 10^{43} erg s^{-1} for Cen A (Whysong & Antonucci 2003; Abdo et al. 2010). Thus, we could allow for a duty cycle of 0.1, and still have adequate jet power. So the jet's interactions with a dense cloud are capable of powering the observed UHECRs. Another way of asking the same question is: can a jet actually catch a sufficient number of particles from the knee region with energies near PeV and accelerate them to the ankle region near EeV to ZeV? Assuming that the energy density of CRs in the starburst region is about 100 times what we have in our galaxy, the particle density near and above 10^{15} eV is about 10^{-17} cm^{-3}. If through the non-steadiness of the jet these CRs are caught at the same rate by a kpc scale jet having an opening angle of, say, 5°, the cross section of $\sim 10^{41.5}$ cm^2 implies a rate of 10^{35} particles accelerated per second. Pushing them to UHECR energies gives an energy turnover of order 10^{42} erg s^{-1} just for the energies above $10^{18.5}$ eV, which is again quite sufficient.

Third, we need to check whether enough time is available for the particles to be accelerated. A jet encounter with such a large cloud would last for at least 10^4 yr (Choi et al. 2007). A shock in either the external or the internal medium would take some small multiple of the Larmor timescale at the maximum energy of a few times $10^{4.3}$ yr, to complete the acceleration process. The two relevant timescales, for transit and acceleration, seem consistent within the scope of our broad estimates.

Lastly, we need to check whether the timescales are long enough so that the time window for possible detection of the UHECR source is not too brief. The time-scales for particle acceleration and the jet–cloud encounter are somewhere between 10^4 and 10^5 yr. The times for the jet to transit a shell and then to move on to the next shell appear to be in a ratio of about 1–10. Therefore, a duty cycle, $f_{\rm int}$, of about 0.1, which is easily allowed for by the above calculation, is actually necessary to maintain a quasi-continuous output of accelerated particles.

3. CONSEQUENCES OF THE JET/CLOUD ACCELERATION SCENARIO

Having shown that the basic model is viable, we now consider some of its consequences.

First, we note that the jet may still be mildly precessing after the episode of the merger of black holes (Gergely & Biermann 2009), in the aftermath of the merger of the elliptical and spiral galaxies comprising Cen A (Israel 1998). Also, the gaseous shell may have its own motion, also due to the preceding merger of the two galaxies. This would naturally explain the observed multiple bendings and flarings of the northern jet in Cen A (Gopal-Krishna & Saripalli 1984; Gopal-Krishna et al. 2003; Gopal-Krishna & Wiita 2010). Both effects would expose continuously fresh material to the action of the jet, but are not an essential requirement for our model.

Second, the transport and scattering of the particles along the way might smooth out any variability even if Cen A were the only significant source of UHECRs in our part of the universe. Such variability might explain the inconsistencies between Auger and HiRes results (Abraham et al. 2010; Abbasi et al. 2010a). The magnetic field at the site of origin is locally enhanced by the Lorentz factor of the shock, possibly between 10 and 50 (e.g., Biermann et al. 2009a). That could imply the shortest possible variability time $\tau_{\rm var} \simeq 100\,\tau_{\rm var,2}$ yr, taking a high Lorentz factor of 50. The scattering near the Earth needed to attain near isotropy in arrival directions requires a relatively strong magnetic field within the distance equal to $c\tau_{\rm var}$. So the containment of Fe particles of up to 3×10^{20} eV would imply an energy content near Earth of $E_{B,\rm var} \gtrsim 6 \times 10^{51}\,\tau_{\rm var,2}^{+1}$ erg. Interestingly, this total energy approaches the energy of a hypernova (10^{52} erg). However, there is currently no evidence for such a region surrounding the Sun.

Finally, we have to follow through with the deduction from the Poynting flux limit (Lovelace 1976) that the highest energy events can only be heavy nuclei if they come from Cen A. This limit requires that all particles caught by a shock in the jet have E/Z less than or equal to that of Fe at $10^{20.5}$ eV, the highest energy event yet seen; let us assume initially, that this one event at $10^{20.5}$ eV is a factor of 3 below the real limit imposed by the acceleration site, the shock in the jet interaction region. It follows that He above $10^{19.9}$ and CNO above $10^{20.1}$ eV are ruled out, but near $10^{19.7}$ eV both are possible. We use the prescriptions of Allard et al. (2008) to define a photo-disintegration distance $\Lambda_{\rm dis}$ for any nucleus and energy. Averaging over some wiggles in the curves that cover both FIR and microwave backgrounds from the very early universe, we find that over the relevant energy and nucleus charge range an adequate approximation is $\Lambda_{\rm dis} = 10^{1.6}\,{\rm Mpc}\,(Z/Z_{Fe})/(E/10^{19.7}\,{\rm eV})^{2.6}$, which we use here to guide us. There are two extreme scattering limits. In one limit, the isotropization of the events from Cen A is done in the intervening intergalactic medium (IGM). Cosmological MHD simulations by Ryu et al. (2008) imply a Kolmogorov approximation; then $\Lambda_{\rm trav} = 10^{1.6}\,{\rm Mpc}\,[(Z/Z_{Fe})/(E/10^{19.7}\,{\rm eV})]^{1/3}$. However, this already leads to extreme losses of the heavy nuclei between Cen A and us. So we consider the other limit, in which the UHECRs travel essentially straight from Cen A to us, and are isotropized in the magnetic wind of our Galaxy (Everett et al. 2008). Modeled values of the wind's magnetic field strength ($\sim 8\,\mu$G) and radial scale ($\sim$3 kpc) allow Fe, as well as all elements down to about oxygen, to be scattered into isotropy; however, there is less effect on lower Z elements. No other approach gave a reasonable fit to the data. The losses due to the path traversed during the scattering are small. A fit with this approach is shown in Figure 1. One could use other magnetic wind model numbers, closer to a Parker-type wind (Parker 1958), but the essential results do not change. Now we must ask: how can this be compatible with IGM models (Ryu et al. 2008; Das et al. 2008; Cho & Ryu 2009)? Given the overall magnetic energy content in the IGM, scattering can be reduced if much of the overall magnetic energy is pushed into thin sheets (Biermann et al. 2009c) and such substructure plausibly arises from radio galaxies and galactic winds. A second question is whether the magnetic field could also produce a systematic shift on the sky for UHECRs, in addition to scattering and isotropizing them. Indeed, any Galactic magnetic field (Beck et al. 1996), in the disk or in the foot region of a Galactic wind (Stanev 1997; Everett et al. 2008), would also produce a systematic shift relative to the central position of Cen A on the sky. Since Cen A is not far from the sensitivity edge of the Auger array in the sky, it is quite possible that there is a shift for all events, especially at slightly lower energies. The models of Zirakashvili et al. (1996) show that angular momentum conservation and transport quickly generate a magnetic field component parallel to the galactic disk, which would shift particle orbits in a direction perpendicular to the disk, and possibly away from the center of symmetry.

A testable prediction of this scenario then is that a solid angle on the sky containing half the UHECR events toward Cen A should show the signature of lighter nuclei, hence larger fluctuations, compared to the events seen from the remaining part of the sky. Since the main scattering also has a systematic component, the center of this anisotropy may be shifted with respect to Cen A, so that the part of the sky with the largest fluctuations in the shower properties may be offset by up to a few tens of degrees from Cen A for $Z > 1$. This effect might be strong enough so that in some parts of the sky lighter elements might predominate over heavies and thus reconcile results from the Auger and HiRes experiments (Abbasi et al. 2010b; Abraham et al. 2010). This could soon be checked with the growing data on UHECRs. If such a test were positive, it would unequivocally and simultaneously show that Cen A is the best source candidate, that scattering depends on the energy/charge ratio, and that the most energetic events are heavy nuclei.

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