SNRs and Cosmic Rays
Breakthroughs and Challenges

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COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington, and California Institute of Technology, Pasadena

Communicated March 19, 1934

D. Conclusions.—From the data available on super-novae we conclude (1) Mass may be *annihilated* in bulk. By this we mean that an assembly of atoms whose total mass is M may lose in the form of electromagnetic radiation and kinetic energy an amount of energy E_T which probably cannot be accounted for by the liberation of known nuclear packing fractions. Several interpretations of this result are possible and will be published in another place.

(2) The hypothesis that *super-novae emit cosmic rays* leads to a very satisfactory agreement with some of the major observations on cosmic rays.

Our two conclusions are essentially independent of each other and should perhaps be judged separately, each on its respective merits.

Three-fold origin of cosmic rays

- Where does the matter come from that gets accelerated?
- Where does the energy come from to power the acceleration process?
- Where exactly is the site of the acceleration?

Three different questions which have sometimes been confused!

Long history of suspected SNR/CR links

- Baade and Zwicky 1934 - remarkably prescient!
- Ginzburg and Syrovatskii 1963 - radio synchrotron emission and energy budget arguments.
  - Definitely GeV electrons in SNRs
  - GCR nuclear luminosity of Galaxy could be supplied by few % of SNe mechanical power.
- DAV 1994 - possible test with gamma-rays from shell-type SNRs

Astron. Astrophys. 287, 959–971 (1994)

ASTRONOMY
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ASTROPHYSICS

The gamma-ray visibility of supernova remnants. A test of cosmic ray origin

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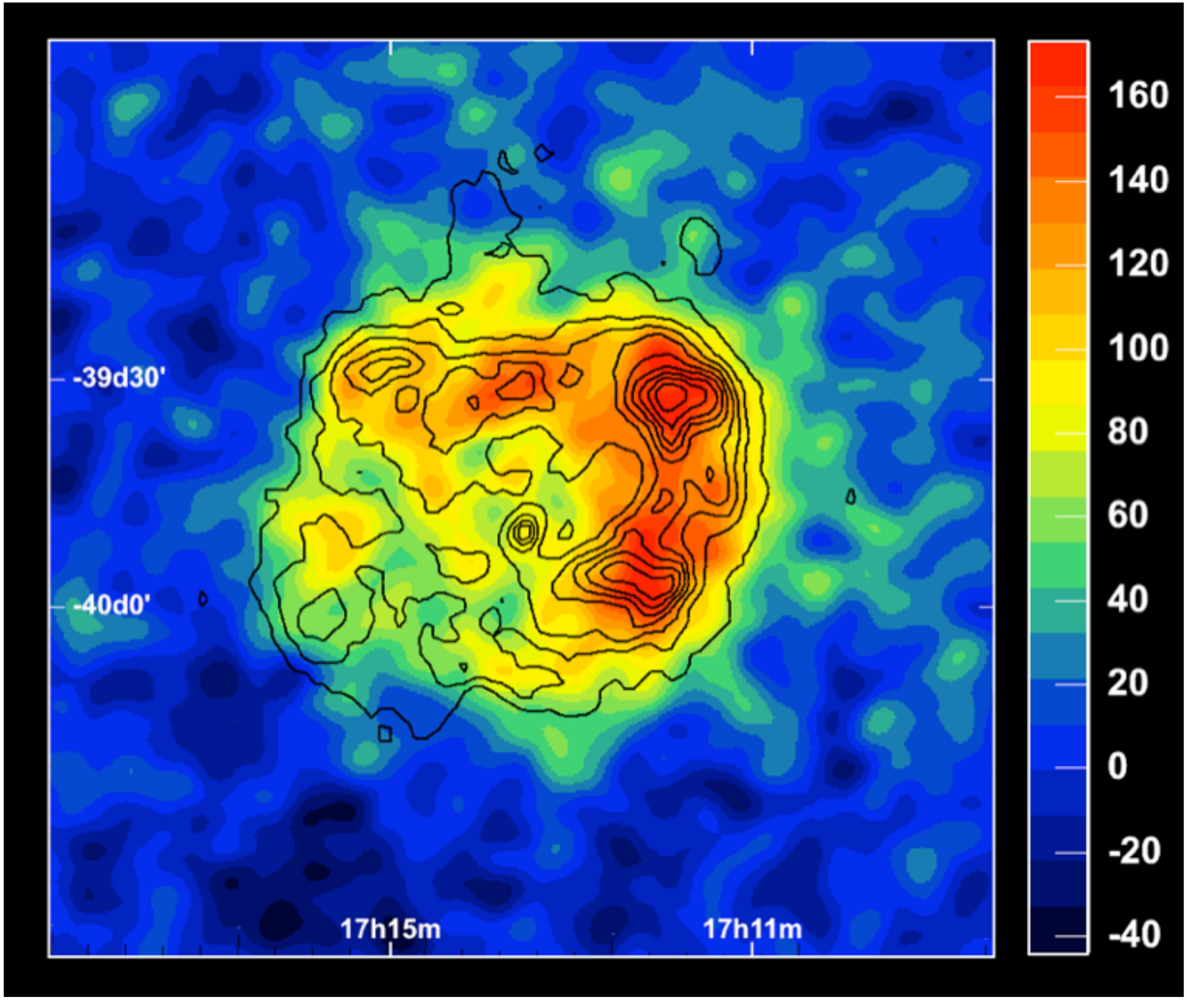
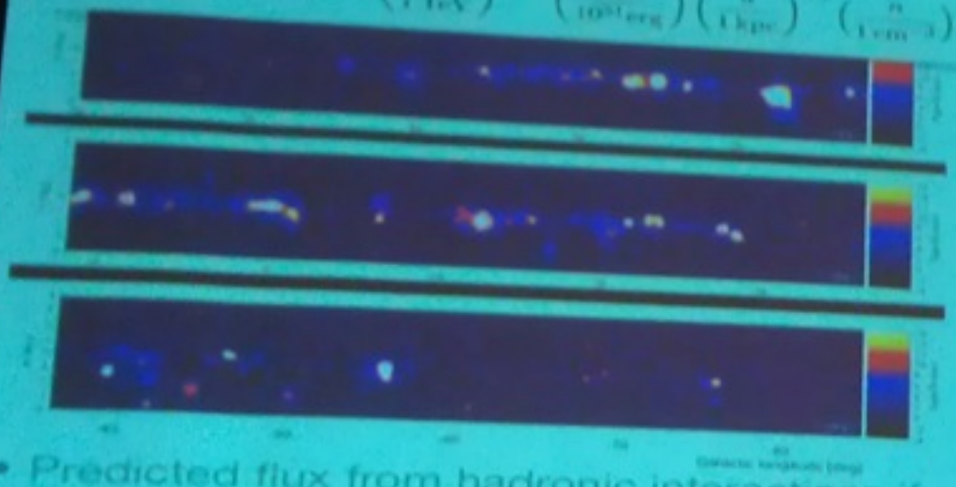
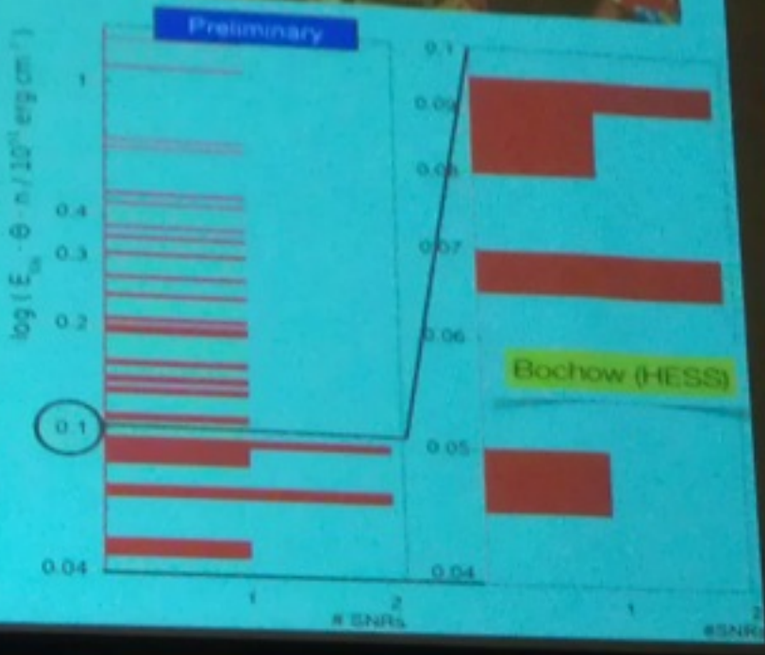
A detailed discussion of instrumental sensitivities and backgrounds shows that detection of SNRs in the $E_\gamma > 100\,\mathrm{MeV}$ band with, for example, the Energetic Gamma Ray Experiment Telescope (EGRET) will be difficult, but should not be impossible. However, and significantly, the prospects look much better in the TeV band accessible to modern imaging atmospheric Cherenkov telescopes. It should be possible to detect SNRs out to distances of several kpc if the region of the ISM into which they are expanding has a high enough density ($n > 0.1\,\mathrm{cm}^{-3}$) so that their γ-ray luminosity is high enough.

Ten years later!



Were Drury, Aharonian, Voelk (aka DAV) right in 1994?

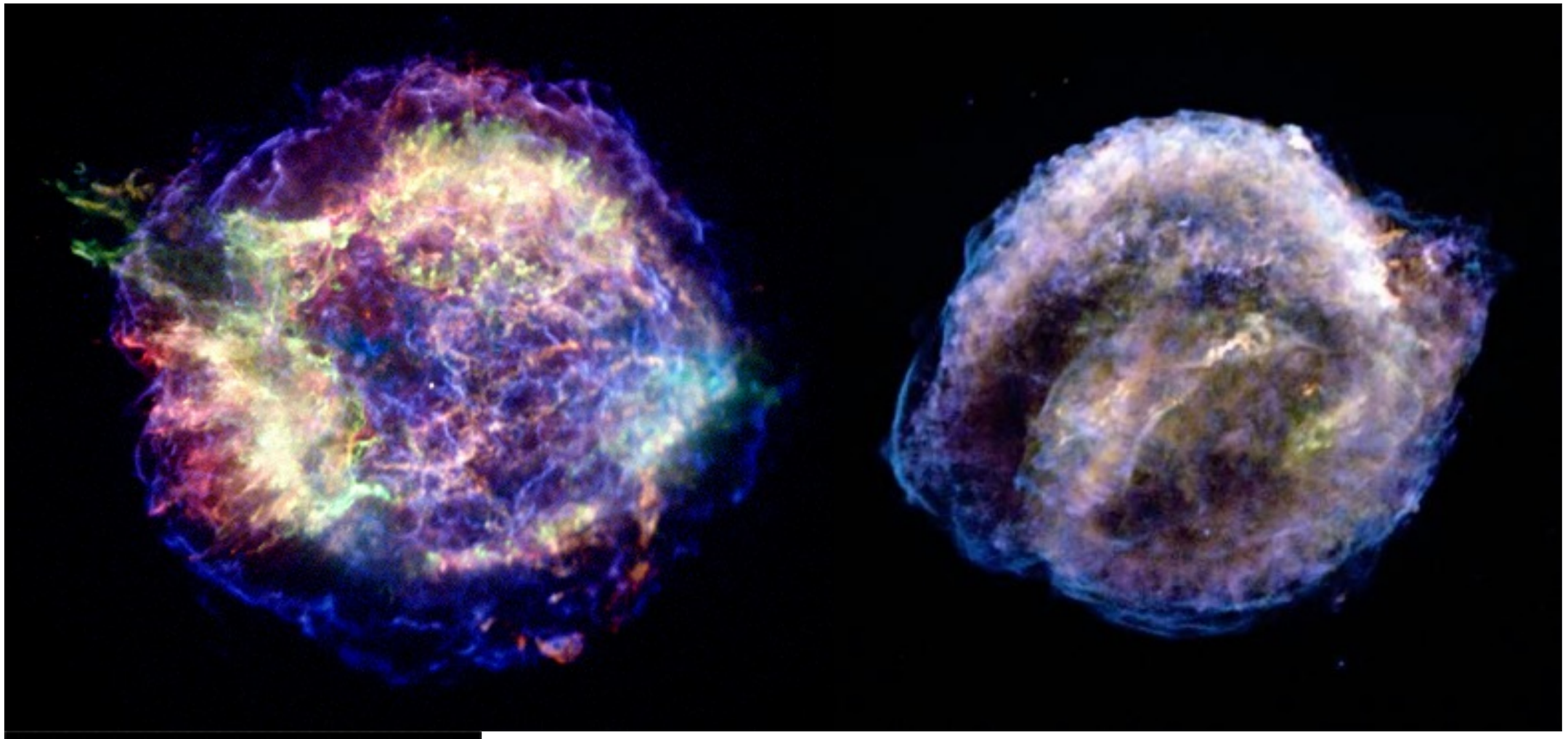




- Predicted flux from hadronic interactions if SNRs were the sources of CRs.
- Predictions are in the right ballpark (D: "DAV survived a falsification test. That doesn't prove it but it makes it more plausible"

Some points

- Adiabatic losses - must be SNR and not SNe.
- Mechanism - answered in 1977 with discovery of DSA by Krymsky et al.
- Still only indirect arguments though…
- Would like to prove acceleration of nuclei as well as electrons to energies well above a GeV.
- X-ray synchrotron emission clearly shows acceleration of electrons to multi TeV energies.
- Separating electronic and hadronic signals surprisingly difficult!



Sharp non-thermal X-ray rims around young SNRs point to TeV electrons and high magnetic fields! Also rapid time variability [Uchiyama et al, Nature (2007) 449 576]

Image mosaic courtesy of Jacco Vink

Recent developments

- Definite proof of acceleration of GeV nuclei in some SNRs through detection of the pion production threshold by both Agile and Fermi (Giuliani, A et al, 2011, ApJ 742 30; M. Ackermann *et al.* 2013 *Science* **339** 807.)
- Fairly convincing arguments that in remnants such as Tycho there is a significant hadronic signal at TeV energies though multi-wavelength models (e.g. Slane et al 2014, ApJ **783** 33.)
- Plausible detection of clouds illuminated by nearby SNRs (W28, IC443 etc).

Breakthroughs

- Definitive evidence for both electron and proton acceleration in at least some SNRs to GeV and TeV energies.
- Strong evidence also for significant (factors of 10 to 100) magnetic field amplification as suggested by Bell and others.
- On theory front, magnetic amplification allows higher energies to be reached in acceleration.

But challenges remain…

- Where are the Pevatrons? All observed TeV emission from SNRs implies proton spectra turning down well before the knee region.
- What is the true production spectrum - tension remains between acceleration theory (favours hard spectra) and propagation theory (softer spectra).
- Why is the knee where it is and how do we get from the knee to the ankle?
- Direct detection of CR precursors in SNR shocks?

A note on maximum energies

- On dimensional grounds expect maximum particle rigidity to be given by BVL - essentially Hillas limit.
- Little that can be done with length scale L and velocity scale V (VL almost constant in Sedov phase) so essentially only hope of higher energies is to pump up B.
- If we take 1 pc, 10,000 km/s and 0.3nT we get a maximum rigidity of 0.1PV.
- But form of GCR spectrum suggests that we need Galactic particles all the way to 100PV.

- So magnetic field amplification is very attractive (also factor 30 available from Fe to p).

- But maximum particle rigidity is one thing - total energy available is another.

- If acceleration is in SNRs then maximum acceleration power occurs when ejecta have swept-up approximately the same amount of mass, ie at start of Sedov phase.

- May accelerate to higher particle energies earlier, but there is less total power available.

Conclusions

- Definite evidence now for both electrons and protons being accelerated in most SNRs to 100TeV, but…
  - Worrying lack of PeV particles (perhaps a selection effect?)
  - Surprisingly and inexplicably (for theory) soft spectra.
  - No real understanding of the origin of the knee to ankle region.
- Need statistical surveys (CTA and friends).