PUBLISHED: 4 JULY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0163

Superdiffusive shock acceleration at galaxy cluster shocks

To the Editor — Low-Mach-number shocks in galaxy clusters give rise to radio relics, bright elongated structures due to synchrotron-emitting electrons, which call for investigation both because of the unclear origin of these energetic electrons and because of their flat radio spectra[1–3]. In a recent Letter, van Weeren *et al.*[4] reported the discovery of a direct connection between a radio relic and a radio galaxy in the galaxy cluster Abell 3411–3412, showing that fossil relativistic electrons originating from an active galactic nucleus (AGN) at the galaxy's centre are re-accelerated at cluster merger shocks. Here we suggest that superdiffusive transport, going beyond the limits of diffusive shock acceleration (DSA), could have a crucial role in explaining the flat radio spectra of re-accelerated fossil electrons. Thus, a theory developed for heliospheric shocks can be widely applied in astrophysics.

Van Weeren *et al.*[4] show that the radio spectral index between 0.325 and 3.0 GHz varies from $\alpha = -0.5 \pm 0.1$ at the galaxy nucleus to $\alpha = -1.3 \pm 0.1$ along the tail; when the radio plasma from the AGN connects to the radio relic, the spectral index flattens to $\alpha = -0.9 \pm 0.1$, providing evidence, together with the brightness increase, for electron re-acceleration at the shock. The corresponding electron energy spectral index is $s = 2.8 \pm 0.2$, where $s = 1 - 2\alpha$. On the other hand, from X-ray Chandra data at 0.5–2.0 keV, a Mach number $M \simeq 1.7$ or lower is inferred, corresponding to a maximum compression ratio of $C \simeq 2$. According to DSA, the energy spectral index for relativistic particles is given by

$$s = \frac{C+2}{C-1} \qquad (1)$$

so that an electron energy spectral index $s \simeq 4$ (or steeper) would be obtained, which is not consistent with the value derived from the radio spectral index $\alpha = -0.9 \pm 0.1$. As for other radio relics[1,2], the inferred Mach numbers are too low to explain the observed radio spectral indices.

Van Weeren *et al.*[4] show that re-acceleration can solve this problem if the fossil electrons have a flat enough power law spectrum with $s = 2.5$ and a Gaussian cutoff. However, a fossil electron distribution so flat may not always be present, so that a deeper understanding of the acceleration mechanism is needed.

A new possibility to explain the observed flat radio spectra is related to the superdiffusive transport of relativistic electrons. In such a case, the mean square displacement of particles grows nonlinearly in time, $\langle \Delta x^2 \rangle \propto t^\beta$ with $1 < \beta < 2$. The extension of DSA to the case of superdiffusion has already been considered for interplanetary shock waves[5,6]. In the superdiffusive case, the energy spectral index for relativistic particles accelerated at a shock is given by[5,7]

$$s = \frac{6}{(C-1)} \frac{(2-\beta)}{(3-\beta)} + 1 \qquad (2)$$

This expression reduces to the standard one for $\beta = 1$ (normal diffusion), while it easily allows hard spectral indices for $\beta > 1$, without the need of a very flat fossil electron distribution. For instance, assuming $\alpha = -0.9$, we have $s = 2.8$, and if a compression ratio $C = 2$ is assumed (as obtained by van Weeren *et al.*) a value of $\beta = 1.57$ is inferred from equation (2). This value of β is consistent with those derived at heliospheric shocks[6,8].

Ragot and Kirk[9] already pointed out that the transport of relativistic electrons in the Coma cluster may be superdiffusive, while Lazarian and Yan[10] showed that cosmic ray superdiffusion can be related to the phenomenon of Richardson diffusion, typical of turbulence for scales smaller than the turbulence injection scale. Therefore, superdiffusive shock acceleration, which has been found to be at work for heliospheric shocks, appears as a mechanism that can explain the flat radio spectra obtained by the re-acceleration of fossil electrons in galaxy cluster shocks. ❐

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Acknowledgements

G.Z. and S.P. were supported by the Agenzia Spaziale Italiana under contract ASI-INAF 2015-039-R.O "Missione M4 di ESA: Partecipazione Italiana alla fase di assessment della missione THOR".

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