Mem. S.A.It. Vol. 83, 38

Memorie della

ISM, cosmic rays, and the shape of the heliosphere

W. Kundt

Argelander Institute of Bonn University, Auf dem Hügel 71, D-53121 Bonn, Germany, e-mail: wkundt@astro.uni-bonn.de

Abstract. Contrary to common wisdom, I propose: Our heliosphere, the stalled windzone of our Sun, is likely a sphere of radius $\lesssim$1lyr whose outer edge, the heliopause, lies far beyond the reaches of the Voyager missions. The heliosphere moves subsonically through the ISM, which latter consists predominantly of cosmic rays, both hadrons and leptons, boosted primarily by all the Galactic neutron stars.

Key words. ISM - heliosphere - heliopause - cosmic rays - GRBs

1. Introduction

In their attempt to acquaint themselves with the cosmic environment of our home planet Earth, scientists have explored parts of the inner solar system including the Earth-Moon system, and even parts of the outer solar system up to the solar wind's *termination shock*, which has been crossed by the Voyager spacecrafts 1 and 2 in December 2004 and August 2007 respectively, at respective distances of {94, 84}AU from the Sun. But we have no measurements yet of the size and shape of the heliosphere – ellipsoidal or cometary – nor have we direct information on the distance of the *heliopause*, and of the (interstellar) medium beyond it. In this talk I shall argue that the heliopause is quasi spherical, of radius $\lesssim$ one light year, and that space around the solar system is filled predominantly (80%) with cosmic rays, interspaced with star-forming clouds (20%) which are often cirrus-shaped, and which lower the effective interstellar sound speed from 2c/3 to near 10^2km/s.

Send offprint requests to: W. Kundt

This interpretation is consistent with several recent maps of the termination shock by energetic neutral atoms (*ENAs*), with the cosmic rays (*CRs*, of all energies) being mainly injected by Galactic neutron stars, both hadrons and leptons, with a non-negligible contribution by the γ-ray bursts (*GRBs*) – which are all of Galactic origin. In particular, the (low-energy) anomalous component of the cosmic rays is of interstellar origin, stemming from all the magnetized accretors. This description of our nearest cosmic environment differs in a number of ways from alternative ones in the literature, cf. Krimigis et al (2011).

2. A large, spherical heliosphere?

Our planet Earth orbits around the Sun at a distance of one AU. It thereby moves (not through vacuum but) through the multi-component solar wind, of present strength $10^{-14}M_\odot$/yr, against which it is screened by its magnetosphere, in the shape of a bowshock with a long, cometary tail that has been traced far beyond our Moon. Jupiter, Saturn, Uranus, and Neptune have similar (cometary) *screening magnetospheres* around them, in contrast to Mercury, Venus, Mars, and most of the ($\geq$172) moons of the solar system. During its helical escape from the Sun – forced by radial and shear stresses – the solar wind's speed passes from subsonic to supersonic at a separation of $\lesssim$ 0.3 AU, and its radial ram pressure p(r) decreases as r^{-2} with distance r until it has dropped to almost interstellar values, $\gtrsim 10^{-12}$dyn/cm^2, at its termination shock, of radius $r_{ts} \lesssim 10^2$AU. From here on, the partially shocked, multi-component solar-wind plasma, of density $n = 10^{-2.7\pm0.5}$cm^{-3}, temperature $T = 10^{5\pm0.5}$K, magnetic fieldstrength $B = 10^{\pm0.2}\mu$G, is thought to cool, and condense to typical interstellar values of 'warm' hydrogen: {$n = 10^{-1}$cm^{-3}, $T = 10^4$K}, on its way out to the *heliopause*, the expected discontinuity surface beyond which lies the ISM, the medium accumulated from the winds of all the other stars in the Milky Way, some of which may even be residuals of the ancient megayears of the Milky Way's formation (Richardson et al., Decker et al., Stone et al., Burlaga et al., Gurnett & Kurth, Wang et al. 2008), cf. Fig.1.

How far out is the heliopause expected to be, and what is its shape? Because of their low densities, outer *windzones* tend to be transparent, hence difficult to map. But young supernova remnants (*SNR*s) are illuminated windzones, heated to X-ray temperatures by the impacting splinters plus relativistic piston of the SN explosion, and Fig.2 shows four of them to be quite spherical. For a dominantly relativistic ISM – as will be further reasoned below – the windzones of all slowly moving stars (like our Sun) are thus expected to be rather spherical, and we can estimate the size of the heliosphere by expanding its accumulated wind matter, $\gtrsim 10^{-14}M_\odot$/yr throughout $10^{9.66}$yr yield some $10^{-4}M_\odot$, from its density inside the Sun ($n_e \lesssim 10^{24}$cm^{-3}) to interstellar density ($n_e = 10^{-1}$cm^{-3}), implying a present heliospheric radius of $10^7 R_\odot \lesssim 10^{18}$cm. The heliopause is thus expected to be coarsely a sphere of radius one lightyear, not to be reached by the Voyagers within the coming 10^4years; an expectation not shared by the scientific community (Krimigis et al. 2011).

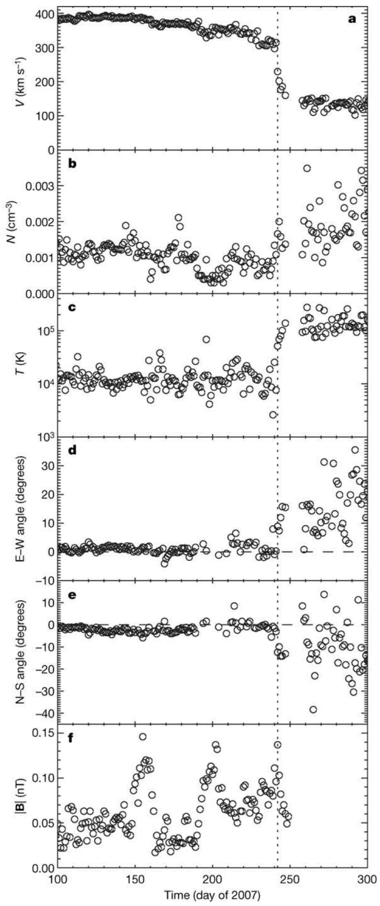

Fig. 1. Solar-wind data measured by Voyager 2 near the solar termination shock in late 2007, copied from Richardson et al (2008): Daily averages of {radial velocity V, number density N, temperature T, magnetic field B: orientation and magnitude}, as functions of time (in days). Note that discrete decelerations of the solar wind were recorded (already) on days 158, 201, and 244 of 2007, seen most clearly as peaks in B, of which (only) the third is called 'termination-shock', even though the jumps in V, N, and B are distinctly sub-Rankine-Hugoniot. Reprinted by permission from Macmillan Publishers Ltd: Nature 454 (p.63-66), © 2008, `http://www.nature.com`

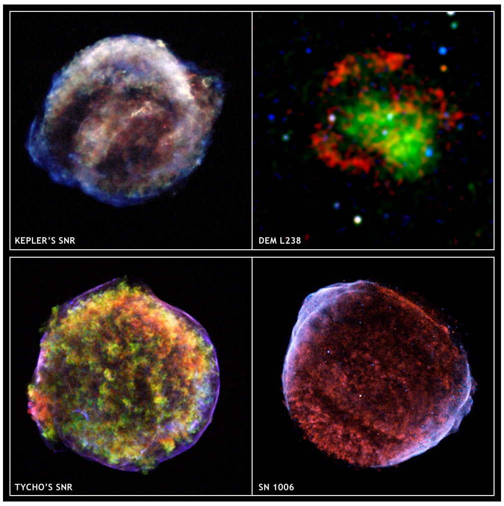

Fig. 2. False-colour maps, at X-rays, of the four young supernova remnants Kepler, DEM L238, Tycho, and SN 1006, copied from NASA. Notice their almost spherical shapes, with (only) occasional lemon-like distortions.

3. Stellar windzones and the ISM

What is the ISM composed of? When we watch the sky, most of what we see of the Milky-Way disk is warm hydrogen and helium. But Ron Reynolds (1990) has told us that warm hydrogen fills only 20% of interstellar space; the rest should be hotter, in order not to be visible in absorption, or even via its gravity (at given pressure). And we know since some hundred years that interstellar cosmic rays penetrate permanently into the terrestrial atmosphere, which have travelled upwind against the solar wind; they are relativistically hot, with peak energies near 5 GeV per ion. We also know that all Galactic (radio) pulsars, and all stellar jet sources inject permanently relativistic pair plasma into the ISM, and that most likely, all accreting X-ray sources inject cosmic rays (Kundt 2008, 2009, 2011). From this and a few further evidences, I concluded in 1997 that our Milky Way should be pressure-supported by relativistic particles, both $e^{\pm}$-pairs, and hadronic cosmic rays.

These expectations have been in agreement with the recent *termination-shock crossings* of the Voyager 1 and 2 spacecrafts referred to in the Introduction; the measured jumps strongly disobey the Rankine Hugoniot constraints: Jumps were repeatedly recorded, up to 0.7 AU (10^2days) before shock crossing (!), during passages of enhanced helical magnetic fields, but unexpectedly less so during the shock transit proper, and even incompletely there. Apparently, both the (outgoing) wind plasma, and the (incoming) ambient plasma are multi-fluid, both charged and neutral, and multi-temperature, which do not move at the same center-of-mass speeds, and traverse each other, so that one large discontinuity is replaced by more than three smaller ones, with weaker transfers (of 4-momentum) each. And in particular, the predicted generation of an '*anomalous component*' of cosmic rays at the termination shock was not encountered, in agreement with my understanding that in situ acceleration is in conflict with the Second Law of thermodynamics (Kundt 1984). Instead, the anomalous component of the cosmic rays continues to increase in intensity beyond shock crossing (of the Voyagers). It appears to be of interstellar origin, as a low-energy tail of the familiar spectrum, of roughly 'white' energy spectrum: $E^2\dot{N}_E$ = const, generated by a multitude of interstellar accretors, see Fig.3.

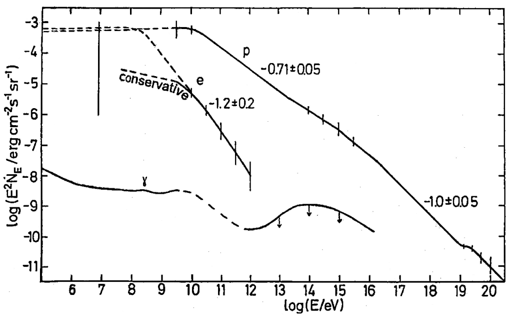

Fig. 3. Spectra of the interstellar Cosmic Rays inferred from terrestrial measurements: ions (p), electrons (e), and photons (γ), plotted double-logarithmically as $E^2\dot{N}_E$ versus E, where E is their energy. Uncertainties are indicated by vertical bars. Broken lines at low energies remind of difficult extrapolations from inside to outside the heliosphere; they concern the 'anomalous component'.

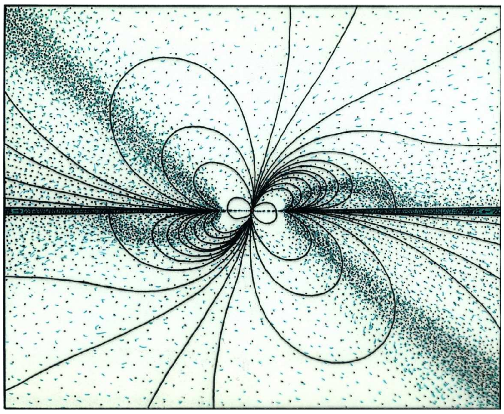

Fig. 4. Sketch of my preferred model for CR acceleration (by a magnetized rotator): Jim Kemp spoke of "magnetic spanking". The inner edge of the (conducting) disk cuts deeply into the magnetosphere, yielding locally higher-than-dipole fieldstrengths. The field tends to penetrate into the disk, diffusively, is strained by differential rotation, and reconfigures quasi-periodically via reconnections. The resulting stick-slip coupling (between magnetosphere and disk) causes sawtooth-type magnetospheric oscillations, with quasi-periodic magnetic reconnections at almost the speed of light. The latter act like relativistic slingshots, boosting charges (from the disk) of either sign up to VHE and UHE energies.

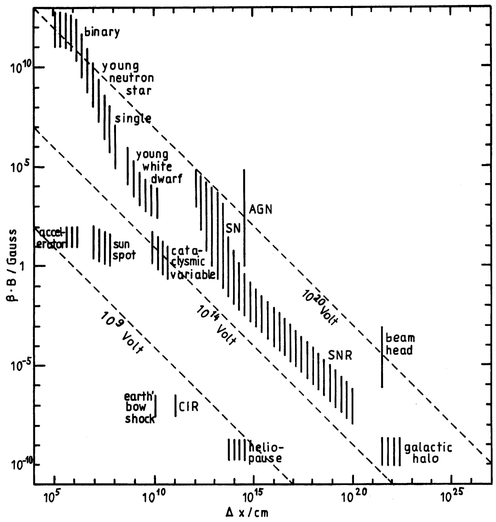

Fig. 5. Modified Hillas plot, cf. integral formula for ΔW in the text. Plotted are the estimated quantities $\beta_\perp$B/G and Δx/cm describing the average Lorentz force e$\beta_\perp$B along a boosting path of length Δx, whose resulting energy is constant along diagonal straight lines (of the plot) marked "10^{20}eVolt" in the highest case. Note that all entries are only necessary estimates, not sufficient ones for successful boosting, (because the integral is not really evaluated), and that single vertical bars stand for scenarios which are judged unsuitable for boosting, (i.e. for which a suitable mechanism is not known).

So how should we visualise the ISM in the vicinity of our solar system? To begin with, every former and present star injected and injects its own windzone, of radius $\gtrsim$1 lyr. Clearly, more-massive stars than our Sun blow more massive windzones, larger by factors $\lesssim 10^2$ in radius, by the same estimate as above. But in addition, there are the compact stars, of degenerate matter, white dwarfs and neutron stars. They are roughly comparable in number to the high-mass stars, and blow much hotter winds. Pulsars: young, fast spinning, isolated neutron stars, blow leptonic bubbles of radius $\gtrsim 10^{15}$cm. All jet sources blow leptonic lobes. In addition, there are all the X-ray binaries, and even the X-ray emitting young pulsars with low-mass accretion disks both of which act similarly to relativistic grindstones, and are likely to generate all the cosmic rays, with typical energies ΔW = $10^{9.7\pm1}$eV, but ranging all the way up to $10^{20.5}$eV, according to the formula (Kundt 2009, 2011):

$$\Delta W = e \int (\mathbf{E} + \beta \times \mathbf{B}) \cdot d\mathbf{x} \lesssim 10^{21}\text{eV}\ (\beta_\perp B)_{12}\, (\Delta x)_{6.5}\ , \qquad (1)$$

cf. Figs.4, 5. This class of neutron stars with hard ejections includes even the GRBursters, which in my understanding are all Galactic magnetars (Kundt 2008, 2010): The bursts result via spontaneous accretion of massive chunks of matter from a surrounding low-mass accretion disk onto the neutron star's surface. In this way, the windzones blown by all the neutron stars add up to much fewer particles in the Galactic disk than those by ordinary stars but of much higher energies, by factors of $\lesssim 10^{10}$, such that they act as the pressurizing, volume-filling medium of the Milky Way,

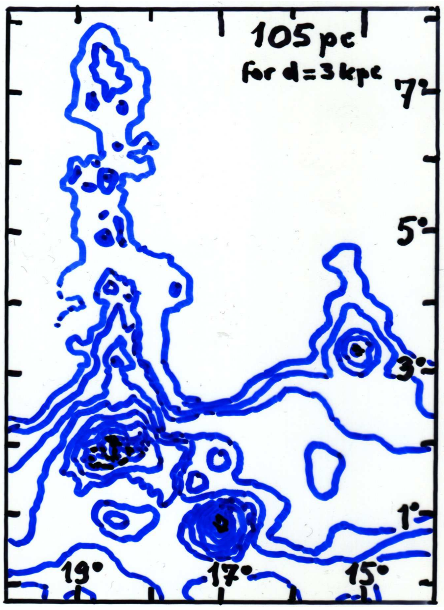

Fig. 6. CR escape into the halo: Stockert's chimney, proposed as the best case of observed CR escape from our Galactic disk into its halo, jointly with hot hydrogen ($T \gtrsim 10^7$K), by Kundt & Müller (1987). The chimney is argued to have formed above the large, high-latitude HII region S54. A few hundred such transient chimneys are estimated to have sufficed to fill the whole Galactic halo with CRs.

and even of its present-day halo (Kundt 1997); whereby they escape into the halo typically after 10^7 years of storage in the disk (Kundt & Müller 1987), cf. Fig.6.

4. Subsonic motion of the heliosphere

The solar system is not only flooded by incoming cosmic rays but also by incoming energetic neutral atoms (*ENA*s), observed between 10 eV and 6 keV : former energetic interstellar ions which approach the Sun and turn into neutral atoms by electron capture, preferentially near the inner edge of the heliosphere, wherafter they perform ordered freefall motions, unaffected by magnetic fields. Many of them get re-ionized in the inner solar system whereupon they are swept out again by the solar wind, as 'pickup ions', formed mainly from hydrogen, helium, and oxygen, whilst the remaining ENAs can be used to map their average infall directions. The pickup ions allow observers to measure the relative velocity of the solar system w.r.t. their average infall speed, of 26 km/s, from a direction denoted 'local ISM', or "nose" for short. A different speed of similar magnitude can be measured w.r.t. the rest system of the nearby stars – the local system of corotation with the Galaxy, called 'solar Apex' – and yet another speed, of magnitude 65 km/s, of the center-of-mass motion of the impacting cosmic rays, which agrees with the direction of the ambient Galactic magnetic field. All three directions are pairwise different, and so are the speeds of the nearby matter systems: Apparently, we deal with local random motions of independent Galactic subpopulations. With these facts in mind, I feel strengthened in my earlier guess that the '*Local Hot Bubble*' which supposedly surrounds our solar system is an illusion, like being surrounded by air (instead of wood) when walking between the trees of a forest. Beyond a certain distance (of order $\gtrsim 10^2$pc), inhomogeneous mass distributions superpose to look increasingly homogeneous, whereas there are strong density contrasts on smaller spatial scales.

Unexpected and still undigested has been the recent discovery by the 'interstellar boundary explorer' (*IBEX*), and confirmed by CASSINI and STEREO A and B, that we receive enhanced ENA radiation (by factors of $\lesssim 6$) from a great circle in the sky whose plane is at right angles to the local direction of the interstellar magnetic field, see the cartoon in Fig.7 (McComas et al., Fuselier et al., Funsten et al., Schwadron et al., Möbius et al., Krimigis et al. 2009). The cartoon indicates not only the various directions (of the 'nose', the 'solar apex', the ambient magnetic field, and the two voyager orbits), but also the possible orientation of a 'heliospheric tail' which to the best of my knowledge is only expected, not observed; the tail may not exist at all. The cartoon maps the quasi-spherical termination shock of the solar wind.

After its termination-shock crossing (on 16 December 2004), within the following six years, Voyager 1 has measured a decreasing ra-

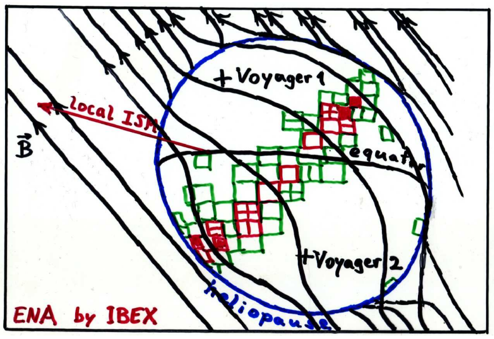

Fig. 7. Our heliosphere interacting with the local interstellar medium (*LISM*): Cartoon of the ribbon on the sky mapped by IBEX via ENAs, redrawn from McComas et al (2009). Shown in red is the inferred 'nose' direction of solar motion through the LISM, in black the local Galactic magnetic field, and as crosses the escape directions of the two Voyager spacecrafts; not marked is the solar apex. Our cartoon ignores a symmetry-violating tail of the heliosphere which to my knowledge had been widely expected but has not been observed. The measured flux of ~keV photons peaks at 400 cm^{-2} s^{-1} sr^{-1}.

dial speed into the heliosphere of all the low-energy ions between 40 keV and 2 MeV, almost linearly decreasing for three years (since April 2007), from initial 70 km/s down to zero (in April 2010), and vanishing thereafter (until February 2011: Krimigis et al. 2011). In my understanding, these low-energy ions have helped condensing the partially stalled, recently added solar wind to the inner heliosphere, with only minor fluctuations to be expected during the millennia to come. Time will tell.

5. Conclusions

This talk, on the geometry and kinematics of our solar system – as a member of our Milky-Way disk – proposes a consistent interpretation of an increasing number of observations by diverse instruments and space missions. In this picture, the heliosphere is a large sphere, of radius $\lesssim$1lyr, coasting subsonically through a multi-component ISM which is pressure-wise dominated by cosmic rays, both hadrons and leptons. The cosmic rays are mainly injected by all the Galactic neutron stars.

6. Discussion

GENNADY BISNOVATYI-KOGAN: Do we need to wait 1000 years if there is a terminate shock?

WOLFGANG KUNDT: Even longer, unless you can find a flaw in my argument: As reasoned in my talk, I expect the heliopause to be spherical and of radius $\lesssim$ lyr. At their speeds of $\gtrsim$3 AU/yr, the Voyager spacecrafts should take $\lesssim 10^{4.3}$yr to reach it.

CARLOTTA PITTORI: Can you please comment about the possible implications of the recent AGILE discovery (confirmed by FERMI) of gamma-ray flares and variability of the Crab pulsar nebula?

WOLFGANG KUNDT: When I heard first about this unexpected measurement of PeV flares by AGILE last December at Heidelberg, I got excited because it opens a new window towards the boosting efficiencies of pulsars. Such irregular outbursts should require a (low-mass) accretion disk around the neutron star.

Acknowledgements. My warm thanks go to Ole Marggraf for the manuscript, and to Hans Fahr and Hans Baumann for (p)reprints and for a number of helpful conversations.

References

Burlaga, L.F. et al. (6 authors) 2008, Nature 454, 75-76
Decker, R.B. et al. (8 authors) 2008, Nature 454, 67-70
Funsten, H.O. et al.(14 authors) 2009, Science 326, 964-966
Fuselier, S.A. et al. (15 authors) 2009, Science 326, 962-964
Gurnett, D.A. & Kurth, W.S. 2008, Nature 454, 78-80
Krimigis, S.M. et al. (5 authors) 2009, Science 326, 971-973

Krimigis, S.M., et al. (4 authors) 2011, Nature 474, 359-361

Kundt, W. 1984, Journal of Astrophysics and Astronomy 5, 277-283

Kundt, W. 1997, in: *The Physics of Galactic Halos*, eds. H. Lesch, R.-J. Dettmar, U. Mebold, R. Schlickeiser, Akademie Verlag, 255-259

Kundt, W. 2008, in: *Multifrequency Behaviour of High-Energy Cosmic Sources*, eds. F. Giovannelli & L. Sabau-Graziati, Chin. J. Astron. Astrophys. Vol. 8, 213-218

Kundt, W. 2009, in: *Frontier Objects in Astrophysics and Particle Physics*, eds. F. Giovannelli & G. Mannocchi, SIF, Conf. Proceedings Vol. 98, 363-382

Kundt, W. 2010, in: *Multifrequency Behaviour of High-Energy Cosmic Sources*, eds. F. Giovannelli & L. Sabau-Graziati, MEMSAIT Vol. 81, No.1, 449-459

Kundt, W. 2011, in: *Frontier Objects in Astrophysics and Particle Physics*, eds. F. Giovannelli & G. Mannocchi, SIF, Conf. Proceedings of Vulcano Workshop 2010, in print

Kundt, W. & Müller, P. 1987, Astrophys. & Space Science 136, 281-287

Möbius, E. et al. (20 authors) 2009, Science 326, 969-971

McComas, D.J. et al. (36 authors) 2009, Science 326, 959-962

Reynolds, R. 1990, in: *Galactic and Extragalactic Background Radiation*, IAU Symp.139, eds. S. Boyer & C. Leinert, 157-169

Richardson, J.D. et al. (5 authors) 2008, Nature 454, 63-66

Schwadron, N.A. et al. (23 authors) 2009, Science 326, 966-968

Stone, E.C. et al. (6 authors) 2008, Nature 454, 71-74

Wang, L., et al. (4 authors) 2008, Nature 454, 81-83