Over the edge?

Len A. Fisk

The two Voyager spacecraft are heading beyond the bounds of the Solar System, and Voyager 1 may now have encountered the 'edge' — the termination shock — of the solar wind. But not everyone agrees.

There is adventure afoot, with controversy to boot. The two Voyager spacecraft were launched by NASA in 1977, and, having explored the outer planets, are now on a path heading out of the Solar System. Voyager 1 is more than 13 billion kilometres away, more than 85 times farther from the Sun than the Earth is. At that distance, argue Krimigis *et al.*[1] on page 45 of this issue, the spacecraft has encountered the so-called termination shock of the solar wind, where the solar wind begins to merge with the interstellar medium. But on page 48, McDonald *et al.*[2] argue equally convincingly that the termination shock still lies ahead. Either way, Voyager 1 has entered a region of our Solar System that has never yet been explored.

The outer atmosphere of the Sun expands continuously into space as a supersonic, flowing plasma of charged particles, known as the solar wind. The wind's velocity is typically between 400 and 750 kilometres per second: in comparison, the speed of sound near the Earth is only 30–50 kilometres per second. As two plasmas do not readily penetrate each other, the supersonic plasma of the solar wind carves out its own volume inside the plasma in the interstellar medium, a volume that is known as the heliosphere.

At some point in the outer heliosphere, however, the solar-wind plasma must begin to merge with the plasma of the interstellar medium. As with all supersonic flows, this merger begins with a shock transition at which the speed drops abruptly, from supersonic to subsonic — just like the shock that precedes a supersonic plane and causes a sonic boom. This is the termination shock of the solar wind (Fig. 1). It surrounds the entire heliosphere, and is by far the largest shock transition in the Solar System. Estimates[3] of the distance to the termination shock from the Sun range from 85 to 120 AU (1 AU, or astronomical unit, is the mean distance between the Earth and the Sun, equivalent to around 150 million kilometres).

The termination shock is expected to be a fascinating astrophysical object and a prodigious accelerator of energetic particles. Interstellar neutral gas penetrating into the inner heliosphere becomes ionized, is picked up by the solar wind and carried into the outer heliosphere. These particles are then accelerated, with their energies increased by a factor of more than 10,000, to form an energetic particle population known as the anomalous cosmic-ray component. It is likely that this acceleration occurs at the termination shock. The accelerated particles can, in turn, exert pressure that alters the structure of the termination shock. In this sense, the termination shock should be similar to shocks in the interstellar medium that result from supernovae, which are also expected to be strong accelerators of energetic particles.

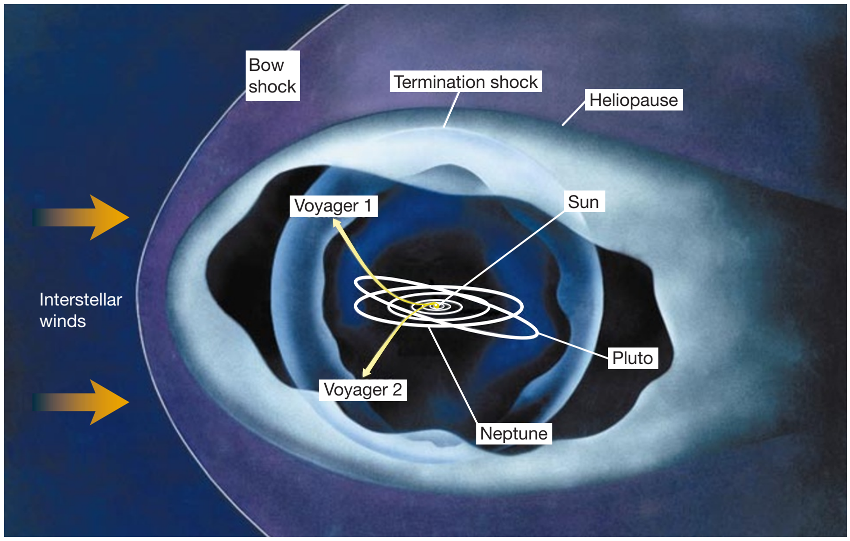

Figure 1 **Fantastic voyage. Voyagers 1 and 2 have flown on different trajectories past the outer planets of the Solar System, and Voyager 1 may[1] — or may not[2] — have reached the termination shock, at 85 AU from the Sun. The termination shock occurs where the supersonic plasma of the solar wind begins to slow down as it encounters the interstellar medium at the bounds of the Solar System. The solar wind and the interstellar medium do not merge easily, so further out, beyond the termination shock, there is the true boundary between the solar wind and the interstellar medium — the heliopause. Further out still, if the Solar System is itself moving supersonically relative to the interstellar medium, there may be a large bow shock.**

If Voyager 1 has encountered the termination shock, there should be several distinct signatures in the data collected by the spacecraft. (Voyager 2 currently trails Voyager 1 by about 20 AU, and has not yet reached the possible location of the termination shock.) The most obvious signature would be the drop in the solar wind speed, with a resulting increase in density and magnetic-field strength. Also, many accelerated particles, particularly the anomalous cosmic rays, should be present.

These two different signatures are the basis for the controversy between Krimigis *et al.*[1] and McDonald *et al.*[2]. The plasma detector on-board Voyager 1, which would have provided a direct measure of the solar wind speed, has not operated for some years. To compensate, Krimigis *et al.* have performed a clever analysis of low-energy particles, and conclude that the solar wind speed has dropped, as required. They also see an increase in the number of these low-energy particles, and of the right types of particle, as would be expected near the termination shock. In contrast, measurements of anomalous cosmic rays at higher energies by McDonald *et al.* imply that these particles must be accelerated at a distance beyond Voyager 1's current position. McDonald *et al.* do see a substantial increase in the intensity of ions and electrons at around 85 AU, but argue that it is only a precursor of the termination shock that still lies ahead.

In fact, the termination shock is not expected to be stationary. Its location will vary with changing heliospheric conditions, which in turn respond to changing solar conditions. Indeed, Krimigis *et al.* argue that Voyager 1 only penetrated beyond the termination shock for around 200 days, after which the shock moved outwards again, leaving the spacecraft back in the supersonic solar wind. The termination shock may well be moving outwards for the next few years, in which case the chase is on again to encounter and study the largest shock transition in the Solar System.

The question is, of course, who's right? Has Voyager 1 already encountered the termination shock? Personally, I tend to agree with Krimigis *et al.*[1] that their data can most readily be explained if the termination shock had been crossed. The data of McDonald *et al.*[2] might then suggest that the termination shock has a more complex shape than expected, or that there is some other means of accelerating energetic particles, beyond the location of Voyager 1. Neither explanation is certain, and we must hope that Voyager 1, on its march ever outwards, will encounter this interesting region again soon.

Once the termination shock has definitely been passed, the adventure enters a new phase. The region of subsonic solar wind beyond the termination shock will be fascinating, characterized by turbulence and particle acceleration, and by many unusual plasma phenomena. The Voyager spacecraft move at 3–4 AU per year, and will eventually encounter the heliopause (estimated to be around 150 AU from the Sun), which is the boundary that separates the solar-wind plasma from interstellar plasma (Fig. 1). Then we will have truly penetrated the interstellar medium. The Voyagers might eventually reach a 'bow shock', caused by the heliosphere itself moving supersonically through the interstellar medium. But both craft will have exhausted their power supply long before that, in around 2020. After a 40-year mission, they will drift quietly into the pristine interstellar space beyond. ■

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1. Krimigis, S. M. *et al. Nature* **426,** 45–48 (2003).
2. McDonald, F. B. *et al. Nature* **426,** 48–50 (2003).
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Evolutionary biology

Scramble for the eggs

Matthew J. G. Gage

Copulating cockerels can, it seems, tailor their ejaculate to several factors: the degree of male competition, whether they have mated with the female before, and the female's reproductive 'value'.

Sperm competition — in which the sperm from more than one male compete to fertilize a female's eggs[1] — is often the final stage in the long struggle for males to reproduce their genes. It's therefore not surprising that it has favoured some remarkable male reproductive traits[2]. One general adaptation is the production of astronomical numbers of tiny sperm, because a fundamental mechanism of sperm competition follows the scenario of a raffle: the males that ejaculate the most sperm are more likely to succeed[3]. But sperm production is not limitless, so males cannot perpetually achieve numerical superiority. Other tricks must be used. For instance, as Pizzari *et al.*[4] describe on page 70 of this issue, cockerels show "unprecedented sophistication" in balancing the need to achieve numerical dominance in sperm competitions, while operating within a limited budget. At each mating, male fowl are sensitive to local social and sexual cues: they produce an ejaculate that is optimized to the level of sperm competition and the female's reproductive value, and which is balanced against their own sperm budget.

Males produce copious numbers of sperm, but the process is costly in many ways. For instance, each sperm cell is under intense evolutionary pressure to be a specialized and competitive DNA-carrying unit. Such specialization may mean protracted periods of production: in mammals, it takes between 5 and 11 weeks (depending on the species) to manufacture a mature sperm cell from the male germ line[5]. In addition, non-trivial energetic requirements have been identified. In adders (*Vipera berus*), for example, the loss of body mass during the sperm-production stage (when males are not physically active) is as significant as that during the ensuing energetic phase of searching, courting, competing and mating[6].

Given these constraints, evolutionary biologists have predicted that males should be prudent in producing an ejaculate, tailoring it to the specific and local demands of each mating[7,8]. Indeed, there is experimental evidence that males can modulate sperm numbers in a seemingly adaptive manner[9–12]. But the study by Pizzari *et al.*[4] reveals that male fowl (*Gallus gallus*) can adjust sperm numbers over more sensitive scales and cues than has been shown before.

The red jungle fowl, and its domesticated descendant the farmyard fowl, has evolved a promiscuous mating pattern in which females mate with several males throughout their fertile window. Males can be either dominant (with full mating access to females) or subordinate (with reduced access). Such promiscuous mating patterns are common across the animal kingdom, with species that evolve true monogamy being in the minority[2]. For males, female promiscuity means that mating success does not guarantee fertilization success.

So how do cockerels increase their chances of fertilizing an egg when competing with rival males? To find out, Pizzari *et al.* studied free-ranging populations of feral and red jungle fowl. The birds were habituated to humans, and females wore a harness that allowed naturally produced ejaculates to be collected and analysed with minimum interference.

In one experiment, which looked at the effects of the degree of sperm competition, cockerels were allowed to copulate in the presence of none, one or three rival males, with increasing male number presenting a rising level of competition. Pizzari *et al.* observed different ejaculatory responses according to the male's social status. Dominant males — predictably — ejaculated more sperm as the risk of competition increased, presumably in an attempt to achieve numerical superiority over their rivals. Subordinate males, however, showed a more complex response: ejaculate size increased when the level of sperm competition rose from low to medium, but fell when the intensity of competition was greatest.

These responses fit closely with two different theories for predicting male ejaculatory responses. Dominant males behave as per a 'risk' model[7], where rising risks demand increasing spermatozoal investment to win fertilization competitions. But subordinate males must play to a more sophisticated 'intensity' model[8]. Low social status means low control over females, so that high numbers of rival males predict very high probabilities of intense sperm competition. Under such scenarios, subordinate males are predicted to reduce their investment and conserve sperm for future matings, because the costs of outnumbering dominant rivals in these sperm competitions are too high. Using the raffle analogy, if there is no competition for the prize, then you buy just one ticket to win; if there is little competition you may maximize your chances by purchasing many tickets; but if the competition is very high, it pays to save your money and buy tickets in a future raffle with improved odds.

Pizzari *et al.* also showed that cockerels were sensitive to the female's comb size, which the authors found to be a predictor of the female's average egg size and hence reproductive 'value'. Thus, males invested more of their sperm budget in females that had larger combs. Similarly, males were sensitive to female novelty. Over successive matings with the same female, a male's ejaculate size progressively fell — indicative of declining sperm reserves. But if a new female was presented to the same male, mating resumed with renewed enthusiasm, and ejaculate size returned to previous high sperm numbers. This reproductive response