magnetosphere. The column momentum impulse of the flow with an assumed depth of 10^{11} cm is 10^{20} g/cm sec, and the disk has a surface mass density Σ of 10^{12} gm/cm². Thus the transfer of momentum from the impacting flow could impart a maximum velocity of about 10³ km/sec to the disk material. Comparison of this velocity with the escape speed from the disk location, which is approximately 10^5 km/sec, indicates that the supernova wind would only buffet the disk and move on. Another way of stating the basic physical reason underlying the stability of the disk is that the flow speed of the supernova debris is comparable to the orbital speed of the disk material, whereas the mass density of the disk, because of tidal effects, exceeds that of the incoming material.

The face-on orientation considered above is too severe. According to the accretion hypothesis for the creation of a millisecond pulsar, material from a nearby star forms a disk that feeds material and angular momentum to the object that becomes the millisecond pulsar. The secondary object that feeds the accretion disk must lie in or near the plane of the disk. Because the remnant disk we propose is formed directly from the accretion disk or from the disruption of the companion, its plane should coincide closely with the plane of the accretion disk. Thus, when the secondary object becomes a supernova, its blast passes by a disk oriented edge on to the explosion, and the actual impulse delivered to the disk is considerably smaller than the most extreme case assumed above.

Finally, the disk could be protected by the magnetosphere of the neutron star. For example, if the magnetic field of a neutron star surrounded by a disk varied as $1/r^3$ from the star to the inner edge of the disk (r, distance from the center of

the star) and as $1/r^2$ beyond that distance (4), the magnetic field of a 10^8 -gauss neutron star at 3×10^8 cm is 4×10^4 gauss. A magnetic field this strong would fully deflect a supernova plasma with a mass density of nearly 0.1 g/cm³. Although we assumed a mass density of 1 g/cm³ as an upper limit for our earlier example, a smaller mass density is likely. However, if the supernova plasma were dense enough to approach the disk closely, eddy currents would be induced in the disk so that the force of the supernova plasma would be transmitted to the disk by magnetic pressure rather than by direct impact (10). Thus we conclude that a durable pulsar disk remains around the neutron star after the accretion and possible supernova events that form a millisecond pulsar.

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- We thank Dr. Ron Elsner and two referees for 11. several helpful comments

27 November 1984; accepted 4 March 1985

Gravity, Drag, and Feeding Currents of Small Zooplankton

Strickler (1) concludes that, for copepods, "gravity helps set up a large feeding current." A copepod "uses its relative weight to create a strong feeding current and takes advantage of the double shear field to perceive its food" (1). However, Strickler does not provide any mechanism by which negative buoyancy sets up a large feeding current and enhances feeding. We suggest a general and testable hypothesis, namely that any retarding force, including gravity or drag, enhances feeding by small planktonic organisms.

Most zooplankters and planktonic lar-

vae of benthic marine invertebrates live in a world dominated by viscosity rather than inertia (2). When viscosity is a dominant factor, there is a thick layer of water that moves with an animal or its appendages that deflects adjacent water with suspended food particles out of its path. Most small planktonic animals swim with cyclical movements of fibers, either appendages or cilia (3), that create a steep velocity gradient near the animal and bring particles within a distance that they may be perceived or contacted. Particles are captured by diverting and capturing the parcel of water containing

suspended particles (4) or perhaps by filtering them from the surrounding water (5). If the fibers producing the current also serve as sensory structures or filters, then increasing flow around the fibers should enhance feeding (6). A restraining force should steepen the velocity gradient around the current-producing appendages (7). An increase in the movement of the appendages relative to the water will result in an increase of close encounters with particles, thereby enhancing feeding. Gravity can provide a retarding force on an upward swimming animal whose density is greater than that of seawater, and thereby create a steeper velocity gradient around the filtering (or water-parcel-capturing) fibers. Drag on a body can also provide an effective tether and operates in any direction the animal moves.

The relative effectiveness of increasing negative buoyancy or drag changes with swimming speed and animal size. At low Reynolds numbers (Re ≤ 1), drag increases in proportion to body length (L) and swimming speed (2). Gravitational force increases with body volume or L^3 . For small swimming animals (about 0.5 mm in length) drag may be a more effective tether than gravity. Let us consider an animal approximated by a prolate spheroid of width one third the length, an excess density relative to seawater of 0.03 g/cm^3 and a swimming speed of 1 mm/sec (8). For an animal 1 mm long, the drag is about 0.6×10^{-8} newton and the gravitational force about $1.7\,\times\,10^{-8}$ newtons so the excess density has three times the effect of the drag (9, 10). An animal 0.6 mm long has a drag force equal to the gravitational force. Many zooplankters and invertebrate larvae are smaller than this.

Planktonic animals bear numerous structures that increase drag. Although these projecting or trailing structures may perform various functions, they also may enhance capture of food while decreasing swimming speed. These structures include mucous strands (11), egg masses, feces (12), and spines (6).

Arrangement of structures for moving water can also greatly increase or decrease drag on the whole animal (13) and also modify flow around structures for sensing or capturing food. For example, appendages and ciliated bands beating toward each other (5, 6) should produce steeper velocity gradients near food capturing or sensing structures.

In conclusion, negative buoyancy or drag could increase fluid motion near food collecting or sensory structures of many small planktonic animals. The effectiveness of increased weight or increased drag depends in part on size and swimming velocity. Different means of increasing the steepness of the velocity gradient can be expected to have different costs. Negative buoyancy requires that an animal swim to keep from sinking and more drag requires more energy to move a given distance. For many small zooplankters there may be a trade between effective feeding and effective locomotion.

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- larvae of 0.1 to 1 mm body length (Hsueh-tze Lee, personal communication). See S. Vogel in (2). Drag force is approximately $C\mu V^{1/3}U$ with a drag coefficient C equal to 11.39, viscosity μ equal to 1.391 × 10⁻³ kg/ m · sec, velocity U equal to 10⁻³ m/sec, and volume V for a prolate spheroid of length three times the width. Increasing swimming velocity or body length will increase the inertial compo-nent of drag force neglected in these colorible. 9. on our rength will increase the inertial compo-nent of drag force neglected in these calcula-tions. For Re >1 and <20, drag force will scale with L to a power greater than 1 and less than 2. Our prolate spheroid has a lower drag coefficient than that for the change of the state of the st that for the shapes of most feeding zoo plankters. F = 1
- For $F_g = (p_0 p_m)$ (V)(a), where F = gravitational force; p = specific gravity of object; $p_m =$ specific gravity of the medium; V = object volume; 10.
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I addressed (1) the paradoxical situation in which herbivorous calanoid copepods, although living in a nutritionally dilute environment (2), must constantly expend energy to maintain their position in the water column to counteract their negative buoyancy. They could, for example, increase their fat reserves to become neutrally buoyant (3). My analysis hinged on the observation that many pelagic calanoids glide horizontally at a constant speed while feeding. Therefore, all forces acting upon an animal [that is, gravity, buoyancy, drag, pressure gradient, torque (1)] result in a small, horizontal force that determines the swimming velocity. Hence, drag acts in the horizontal direction only. The vectors in the vertical direction cancel each other; gravity is counterbalanced by buoyancy and the vertical component of the pressure gradient. The existence of this equilibrium allowed me to conclude that the more negatively buoyant an animal is, the larger the feeding current it can produce.

Emlet and Strathmann (4) apply what is known about the feeding ecology of calanoid copepods (5) to all small zooplankters. Their scaling model points to the importance of gravity to animals larger than 0.6 mm and of drag to the smaller ones. This is in agreement with my conclusions (1) since my calanoids were 1 to 5 mm in length [figure 1 in (1)]. Juvenile calanoids, however, are smaller than 0.6 mm. In testing Emlet and Strathmann's hypothesis I reevaluated some of my older cinematographic observations that suggest that nauplii and early copepodite stages may use drag as the retaining force. As a consequence, these animals do not orient themselves with respect to gravity nor do they exhibit horizontal feeding bouts.

The shear field of the feeding current enhances perception of suspended food particles. Calanoid copepods use two sensory modes, chemoreception and mechanoreception, to perceive food items (6). Chemoreception has not only been suggested for gustatory selection of food items (7) but also for long-range detection of algae suspended in the inflowing feeding current (8). The feasibility of olfaction as a sensory mode was demonstrated with a computer model (9). This model considered production. diffusion, and decay of the chemical signal as well as the laminar, shear-stressed flow field of the feeding current. To test whether dissolved chemicals are perceived, fine trails of the chemicals were introduced into the feeding current, showing that calanoids can detect and track these traces (10). In another set of experiments the environment surrounding the animal was swamped with chemicals, rendering olfaction useless. However, the animal was still able to capture and handle particles with the highest precision (6). These experiments revealed that calanoids may employ mechanoreception using the rigidity of inflowing particles. When entering the shear field of the feeding current or the boundary layer around the mouthparts, the particles are not deformed. Instead, the particles would exert small forces on the animal which might then be detected (6).

Unifying principles may emerge from the comparison of calanoid copepods with other small (sizes in the order of millimeters) zooplankters, such as the larvae of molluscs, barnacles, polychaetes, and benthic crustaceans. However, there could be an inherent difference between holo- and meroplankton. For example, the different species of calanoid copepods adhere to the same basic body plan, thereby presenting many variations on the same theme (11). Larvae, in contrast, show many different kinds of evolutionary life-history strategies and body plans; they are transients within the planktonic community.

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15 March 1985; accepted 22 March 1985