

of a critical velocity for the disappearance of stick-slip motion. Yet the difference in particle sizes is five orders of magnitude. This suggests that these observations may be very general and may even apply to earthquakes and the motion of plates."

The dynamics of sheared foams is similar in some respects to that of granular layers. Anthony Gopal and Douglas Durian (UCLA) have shown that foams flow by sudden stick-slip-like rearrangements involving a flow of the many bubbles within a sheared layer.⁶

At the Ecole Normale Supérieure, Baumberger, Heslot and their collaborators have studied friction between relatively smooth solids such as paper sliding on paper. These materials have asperities (slight irregularities), so they touch only at high spots. The experimenters found stick-slip motion at low speed, and they also found a critical speed that depended on the stiffness of the spring they used. In both cases the transition was discontinuous, and the experimenters said they believed that local contacts were important. As the materials remained in contact, localized contacts tended to strengthen and the coefficient of static friction increased. They also observed creep before a slip event. A theory of this friction has been developed by Christiane Caroli and Philippe Nozière involving plastic deformation of these point contacts.

Jacqueline Krim (Northeastern University) has been exploring frictional forces at the atomic level between crystalline solids. She adsorbs layers of atoms on a (111) metal surface electrode of a quartz microbalance, and then monitors the degree of sliding of the atoms relative to the horizontal oscillatory motion of the atoms relative to the motion of the microbalance. The degree of sliding is determined by the frictional forces.

At McGill University, the studies of Stuart Savage on granular flow anticipated much recent work by physicists

on powder flow. For example, in 1984 he studied stresses developed by dry granular materials rapidly sheared in an annulus. He varied the normal load and showed the effects of dilatancy on the system, and he could examine the geometrical profile of the flow.

Earthquake faults and stress chains

Many geophysicists have studied granular friction in the laboratory under high pressure (kilobar) conditions appropriate to earthquake faults.⁷ Central findings include the observation of creep, the weakening of frictional forces during slip, and the reduction of particle sizes with time. Numerical studies are also being widely used to explore sheared granular layers under geophysical conditions. These studies allow detailed "observation" of the motions of individual particles in the interior of the layer.

Some geophysicists are interested in exploring how the Haverford results on granular friction relate to the "rate/state" behavior (where the friction is expressed as a function of the strain rate and the distance moved).

Eight years ago, a model of earthquake faults was developed by Jean Carlson and James Langer (University of California, Santa Barbara) and Bruce E. Shaw (Lamont Doherty Observatory).⁸ Their deterministic model, based on a block and spring model, had a velocity-dependent friction term. As Langer explained, he and his collaborators "had in effect considered a system consisting of many Haverford experiments coupled together so that stick-slip events could occur at different places in the system on a wide range of scales. This deterministic model then exhibited truly chaotic behavior similar to that observed in real earthquakes. Of course, geometrical and structural disorder, which is omitted from the model, is also important for describing earthquakes."

A group at the University of Chicago has studied the formation of stress chains when a stress is applied to a

dense granular material. Stress chains are approximately linearly aligned sets of grains that carry large amounts of the total force and can extend over many grain diameters. In 1995, Susan Coppersmith and her collaborators at Chicago developed a model for force fluctuations in bead packs and carried out experiments to characterize the statistical properties of static stress distributions.⁹ Says Coppersmith, "Our model for the force chain distribution simply assumes that a given bead randomly divides the weight on it among the beads on which it rests. The model predicts an asymptotically exponential force distribution, as seen experimentally." Says Nagel, "The Haverford group may be measuring what happens when the force chains break." Recently, Robert Behringer and his collaborators at Duke University reported experiments¹⁰ on force fluctuations in sheared systems, which showed stress distributions similar to those predicted by the Chicago model.

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Hipparcos Parallax Data May Reconcile Ages of Globular Clusters and the Universe

In the summer of 1989, the European Space Agency launched the High Precision Parallax Collecting Satellite—Hipparcos, for short. The name of this first automated astrometry orbiter honors Hipparchus of Nicea, who diligently compiled a catalog of the celestial positions and brightnesses of more than a thousand stars in the second century BC.

The number of stars for which we have accurate distances has suddenly grown a hundredfold. It's already affecting estimates of the age of the cosmos.

Two months ago, ESA finally published its catalogs of Hipparcos parallax and brightness measurements for

over a million stars. This compilation represents an enormous expansion of our direct knowledge of the distances to stars out to about 500 light-years and, by indirection, the reliability of estimated distances to much further objects of great astronomical interest.

Early analyses of the Hipparcos data already appear to be softening the troubling paradox that globular star

clusters in our Galaxy seem to be older than the age of the universe implied by measurements of the Hubble constant.^{1,2} (See PHYSICS TODAY, May 1996, page 18.) But other early results are less comforting: The Hipparcos data tell us that some “open clusters,” like the familiar Pleiades, are closer to us than had been thought, implying that stars in these clusters very much like the Sun in mass and metal content are, unaccountably, 30% fainter than the Sun.³ For theorists of stellar evolution, that’s quite unsettling. (In this game, anything heavier than helium is called a metal. The oldest stars are the most metal poor.)

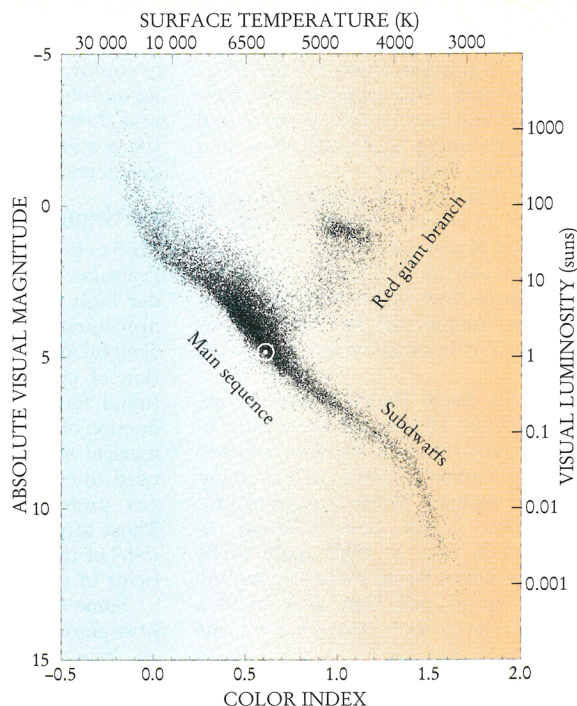
A shaky start

Hipparcos got off to a rather inauspicious start. After a perfect launch by a French Ariane rocket, a booster engine that was to place Hipparcos into a stable geosynchronous orbit failed, leaving the satellite in a highly elliptical orbit that plunged into the perilous Van Allen belt twice in every 11-hour orbit. Fortunately, however, Hipparcos’s solar panels suffered less radiation damage than had been feared from the Van Allen belt, and much reprogramming, rescheduling and the enlistment of ground stations around the globe saved the astrometric mission. By the time Hipparcos fell silent in 1993, its wide-field telescope had harvested 100 gigabytes of stellar position data.

This prodigious data set was so thoroughly intertwined that parallaxes of individual stars could not be extracted until the raw measurements had been completely analyzed, as a single block, just a year ago. The result is two catalogs: The primary catalog, *Hipparcos*, lists 118 000 stars with milliarcsecond astrometric resolution and photometric precision of 0.2%. The auxiliary catalog, named *Tycho* in honor of the last great naked-eye astrometer, contains a million less-well-measured stars, with astrometric resolution of 2.5 milliarcseconds and photometric precision of 6%.

Milliarcsecond astrometric resolution simply means that one can determine the celestial position of the centroid of a star’s image that well. (Resolving features of extended objects is another matter. Even the Hubble Space Telescope cannot resolve features much smaller than 0.1 arcseconds.) If a star’s position on the celestial sphere shifts by 10 milliarcsec, due to parallax, from January to July, its distance from us is 100 parsecs—approximately 300 light-years. Before Hipparcos, only about 100 nearby stars had parallax-measured distances

FIGURE 1.
HERTZSPRUNG-RUSSELL DIAGRAM of 20 853 nearby stars whose distances were determined to better than 10% by Hipparcos parallax measurements. It is a scatter plot of luminosity (at visual wavelengths) vs. surface temperature. A star spends most of its life on the main sequence, at a fixed position determined by its mass and metal content. The lightest, longest-lived stars are at the bottom. The solar symbol indicates our Sun. When its primary fuel is gone, a star wanders off toward the top right. (Courtesy of European Space Agency)



known to within 5%. Now there are more than 7000.

How old?

How long has it been since the Big Bang? The most direct way to address t_0 , the age of the universe, is to measure H_0 , the Hubble constant. The starkest lower limit constraining t_0 is the age of the oldest globular clusters in the Galaxy. Prior to Hipparcos, there was an obvious conflict: Applying standard cosmological models to typical determinations of H_0 yielded ages from about 9 billion to 12 billion years for the universe as a whole. On the other hand, the best estimates of the globular cluster ages ranged from 16 to 18 billion years. It was enough to shake one’s faith. But the new Hipparcos distance determinations are relevant to both ends of the discrepancy, and early analyses are tending toward reconciliation.

Caltech astronomer Neill Reid, in a recent *Astronomical Journal* paper,¹ avails himself of Hipparcos data to argue that the globular clusters are only 11–13 billion years old. Globular clusters are dense aggregates of very old stars in the halo surrounding the Galactic disk. It is not clear whether all the globular clusters are equally ancient, but it is clear that all the stars in any one cluster were born at about the same time in the early days of the Galaxy.

The standard way of determining the age of such an isochronous aggregation of stars is to see where its

Hertzsprung–Russell (H-R) diagram wanders off the “main sequence.” An H-R diagram is a scatter plot of absolute visual magnitude (a logarithmic measure of intrinsic luminosity) against a color index that indicates surface temperature. Stellar evolution dictates that the stars lie along discernible paths in this luminosity–color plane, rather than being randomly distributed. Figure 1 is the spectacular overall Hipparcos H-R diagram for the 21 000 stars for which the satellite’s parallax measurements determined the distance to better than 10%. “It’s the most precise H-R diagram ever compiled,” says Hipparcos project scientist Michael Perryman (Leiden University). Knowing distances is, of course, crucial for converting apparent brightness to absolute magnitude.

A star spends most of its life at a fixed point, determined primarily by its mass, on the main sequence; the heaviest stars are at the hot–bright end (upper left) and the lightest stars are at the cool–faint end (lower right). Late in life, when a star has used up its primary fuels (hydrogen and helium), it migrates off the main sequence toward the upper right—the domain of the red giants.

Figure 1 has stars of all ages. The heavier a star is, the less time it spends on the main sequence. The lightest stars use up their fuels most slowly. Therefore, if one has a population of stars all of which have the same age (and metal content), its H-R diagram peels off to the right of the main se-

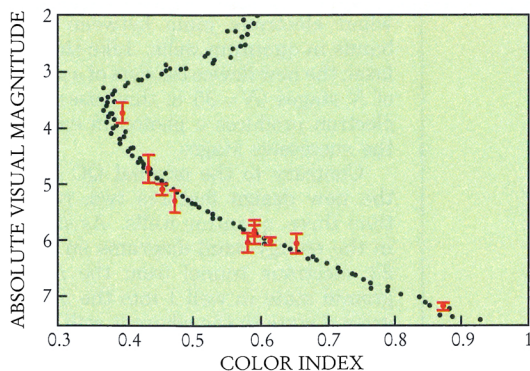


FIGURE 2. HERTZSPRUNG-RUSSELL DIAGRAM of four very metal-poor globular clusters in the Galactic halo. The absolute magnitude at which the distribution turns right, off the main sequence, measures how old these isochronous clusters are. The cluster stars (black points) are too far away for Hipparcos parallax measurements, but the absolute magnitude scale has been adjusted to bring their main sequence branch into line with nearer subdwarfs of the same metal content (red points), whose distances were measured by Hipparcos. (Adapted from ref. 1.)

quence at a well-defined point, above and to the left of which there are no more stars remaining on the main sequence. The turnoff for such an isochronous population, as shown in figure 2, leads onto a much narrower path than the broad red-giant branch seen in figure 1. Figure 2 is the H-R diagram for four very old globular clusters, presumably all being roughly the same age. The low-mass stars remaining on the main sequence are in the realm of the “subdwarfs.”

Recalibrating the subdwarfs

The absolute visual magnitude at the turning point tells us, with the aid of astrophysical models, the age of the isochronous population. The older the population, the farther down the main sequence (toward the lightest, slowest-burning stars) is the turnoff. But these age determinations depend sensitively on how well the absolute magnitudes are calibrated.

Living well outside the Galactic disk, in the halo, the globular clusters are all too far away for direct Hipparcos distance determinations. So Reid took Hipparcos distance determinations for 15 nearer halo subdwarfs with the same low metal content as the oldest globular cluster stars and used them to recalibrate the absolute visual magnitude scale of the subdwarf main sequence in the globular-cluster Hertzsprung-Russell diagram.

The stars showing red error bars in figure 2 are the nearby calibrating Hipparcos subdwarfs. Because all the stars in a given globular cluster are at essentially the same distance from us, and the magnitude scale is logarithmic,

a decreased age estimate of 11–13 billion years.

The Hubble constant

Reid's recalibration also bears directly on estimates of the Hubble constant and the age of the universe. If distant, highly redshifted galaxies are farther away than previously thought, H_0 becomes correspondingly smaller and thus the cosmological models yield greater ages for the universe. The cosmological distance scale depends, at its base, on estimates of the intrinsic luminosities of “standard candles” nearer home.

Among the most important local distance indicators are variable stars such as Cepheids and RR Lyraes. Reid's result pushes the RR Lyraes in the globular clusters farther away, implying that all RR Lyraes are intrinsically brighter and more distant than

one recalibrates the globular cluster H-R distribution simply by shifting it up or down the absolute magnitude axis until one gets the best fit with the calibrating Hipparcos subdwarfs. The assumption, of course, is that halo subdwarfs of a given low metal content will lie precisely on the same main sequence, irrespective of whether or not they are in the globular clusters.

Reid concludes that the four oldest, metal-poorest globular clusters in his study are in fact 15% farther away than was believed before Hipparcos. That corresponds to a 30% increase in intrinsic luminosity and consequently

previously thought. Michael Feast (University of Capetown) and Robin Catchpole (Royal Greenwich Observatory) reach much the same conclusion about Cepheid variables.² Using Hipparcos parallax measurements of some 200 Cepheids, they argue that estimates of H_0 , most of which rest heavily on Cepheid variable observations, must now be reduced by about 10%. That would bring the age of the universe up to about 10–13 billion years, further easing the conflict with the globular cluster ages.

Not everyone agrees. John Fernley (International Ultraviolet Explorer Observatory, Madrid) and coworkers have used Hipparcos measurements of the “proper motions” of 144 relatively nearby RR Lyrae stars to determine their distances by what is called statistical parallax.⁴ Only RR Lyrae itself, the archetype of the class, is close enough for trigonometric parallax. For the others, one measures angular velocities across the celestial sphere and determines the mean distance of the sample by assuming that the Doppler radial velocities of these halo stars are statistically equal to their transverse velocity components. Fernley and company conclude that the pre-Hipparcos calibration of the RR Lyrae absolute magnitude needs no revision. In particular, they disagree with the Feast-Catchpole assertion that the assumed distance to the Large Magellanic Cloud, an important rung on the cosmological distance ladder, needs to be increased.

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Infrared Laser Illustrates Another Way to Achieve Gain

The standard way to build a laser is to produce a population inversion between an upper and a lower energy level. But laser gain is proportional not only to the population difference between two states but also to the oscillator strength, which depends on both the energy difference between the upper and lower states and the probability of a transition between them. By focusing on these often-overlooked factors, a group at Bell Laboratories, Lucent Technologies, has made

Thanks to an innovative design, researchers have made an infrared semiconductor laser whose wavelength can be electrically tuned.

a semiconductor infrared laser with a unique property: It is electrically tunable over a 6% range.¹

Like the quantum cascade (QC) laser developed at Bell Labs by the same team, (see *PHYSICS TODAY*, July 1994, page 20) the new laser emits photons