1

Icarus

On June 26, 1949, Walter Baade discovered a faint streak on a 1-hour star-field exposure (frontispiece) taken with the 48-inch Schmidt camera at Palomar Observatory. This heavenly body, tagged (1566) Icarus (ĭk′ ər əs), and sometimes called Baade's body, is classified as an Apollo asteroid, that is, an asteroid whose orbit crosses that of the earth. At the time of its discovery, and again on June 14, 1968, Icarus passed within 4 million miles of the earth. Within the past 35 years, 3 other Apollo asteroids—Apollo, Adonis, and Hermes—have missed the earth by 2 million, 1 million, and 0.5 million miles (just twice the distance to the moon), respectively. The fact that these Apollo asteroids pass relatively close to the earth, in terms of interplanetary distances, has generated considerable interest in them around the world, and in some cases even grave concern.

Since the Apollo asteroids are relatively small, typically a mile in diameter, and since they pass the earth so quickly, at speeds of perhaps 20 miles per second, they are visible for at most a few hours at a time, even with the largest of telescopes. This limited observation time makes it difficult to obtain sufficient data for calculation of the orbits of the bodies. Icarus, however, has been observed on enough occasions since its discovery to insure the calculation of its orbit to within approximately 150 miles. One of the unique properties of this orbit is the ratio of its period to that of the earth, 19 to 17, which results in a near miss every 19 years. It is thus important that future generations keep a wary eye on Icarus to allow time for preparation should a collision become imminent.

Of course, a collision with Icarus or with any other Apollo asteroid in the near future is highly unlikely. Perhaps the only way in which the present orbit of Icarus can be perturbed into a collision orbit is by a glancing blow from some other asteroid as Icarus streaks through the fringes of the asteroid belt beyond Mars. Such an occurrence is improbable—but not impossible. Perhaps more frightening is the fact that the discovery of the Apollo asteroids by accident, under the most favorable conditions for observation, indicates that most of them whiz by undetected and perilously close to the earth. It should be re-emphasized at this point that a collision between an asteroid and the earth is unlikely to occur soon; Watson, for example, has estimated that such a collision is unlikely to occur more often than once every 100,000 years (1).

But there is evidence that meteoritic impacts have occurred in recent geological times; the Barringer Crater in Arizona, 4,200 feet across, is believed to have been formed on impact between 5,000 and 50,000 years ago. Other rimmed circular depressions like the Richat Structure in Mauritania, 75 miles across; the Vredefort Ring in South Africa, 85 miles; Manicouagan Lake in Canada, 40 miles; Hudson Bay in Canada; and even the entire Pacific Ocean may have been formed by the impact of gargantuan projectiles millions of years ago.

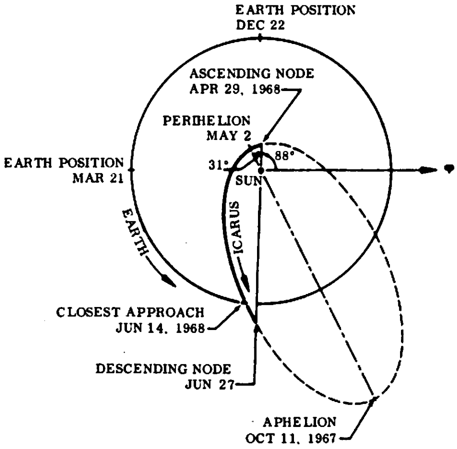
The consequences of a collision with Icarus are unimaginable; the repercussions would be felt the world over. In dissipating the energy equivalent of half a trillion tons of TNT, 100 million tons of the earth's crust would be thrust into the atmosphere and would pollute the earth's environment for years to come. A crater 15 miles in diameter and perhaps 3 to 5 miles deep would mark the impact point, while shock waves, pressure changes, and thermal disturbances would cause earthquakes, hurricanes, and heat waves of incalculable magnitude. Should Icarus plunge into the ocean a thousand miles east of Bermuda, for example, the resulting tidal wave, propagating at 400 to 500 miles per hour, would wash away the resort islands, swamp most of Florida, and lash Boston—1500 miles away—with a 200-foot wall of water.

In light of the consequences of a collision with an asteroid the size of Icarus, the possibility of such a collision, no matter how remote, cannot go unrecognized. The world must be prepared, at least with a plan of action, in case it should suddenly find itself threatened by what had so recently been considered a folly. Thus Project Icarus was conceived. Icarus would collide with the earth in just 70 weeks from the project's inception—unless, of course, the project team, carefully handpicked at the Massachusetts Institute of Technology, could successfully complete its mission. No funds or manpower would be spared; the resources of the nation and of the world were at the disposal of this select group of scientists and engineers.

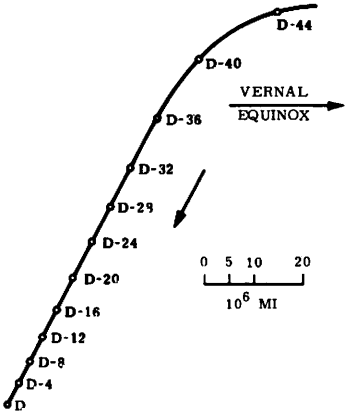
As the study progressed, the intricacies of a realizable solution became more and more evident. But the members of the Project Icarus team, recognizing the remote possibility of disaster, pursued a solution with relentless determination. This determination resulted in what the team felt to be much more than a pure academic study; it resulted in a solution to a problem perhaps more imminent than anyone realizes, and the goal of that solution is the most rewarding of all goals—the saving of human lives.

The Orbit of Icarus

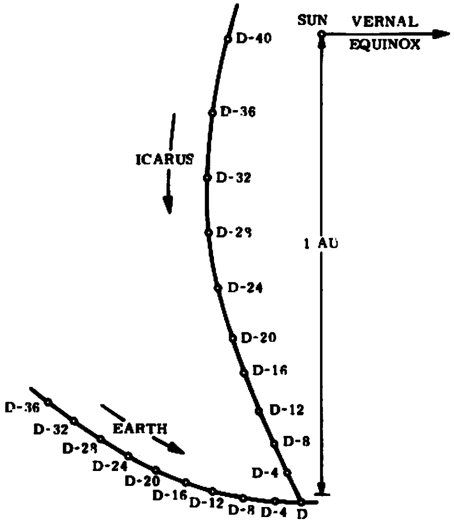
In its present orbit of eccentricity 0.83, Icarus at perihelion passes twice as close to the sun as does Mercury, while at aphelion it reaches past the orbit of Mars, almost to the common asteroid belt, about 2 astronomical units from the sun. Its orbital plane is inclined 22° to that of the earth such that Icarus approached our planet in 1968 from above the ecliptic plane (fig. 1.1) at a speed (relative to the earth) nearly equal to the earth's orbital speed, approximately 18 mi/sec. The true orbital elements of Icarus' path were altered such that impact would occur at noon in the mid-Atlantic, about 1000 mi east of Bermuda, on June 19, 1968. Projections of the



1.1
Orbit of Icarus, 1968



1.2
Ecliptic projection of collision orbit (seen from earth)

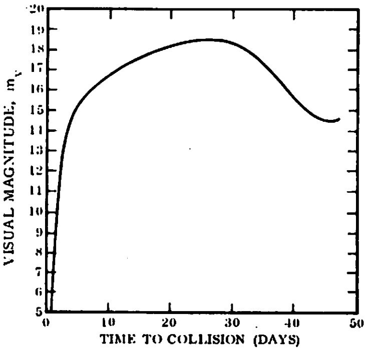


1.3
Ecliptic projection of collision orbit (seen from sun)

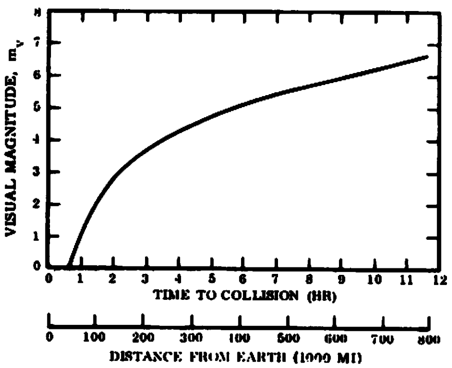
hypothetical collision orbit on the ecliptic plane, as seen by observers moving with the earth and with the sun, are shown in figs. 1.2 and 1.3, respectively.

Brightness and Visibility of Icarus

The brightness of a planet or asteroid (as seen from the earth) varies inversely as the square of the distance from the asteroid to the earth, inversely as the square of the distance from the asteroid to the sun, and directly as the fraction of its visible surface which is illuminated by the sun (that is, the phase of the asteroid). By assuming that Icarus is a perfect sphere, that exactly one-half of its surface (that is, a hemisphere) is illuminated by the sun, and that sunlight is uniformly scattered from the illuminated surface, one can derive a brightness curve from the geometry of Icarus' orbit and from a brightness measurement at a known time. Figure 1.4 shows the brightness variation during the 50 days before collision in terms of visual magnitude, m_v. Although at its dimmest



1.4
Visual magnitude of Icarus (from 50 days to collision)

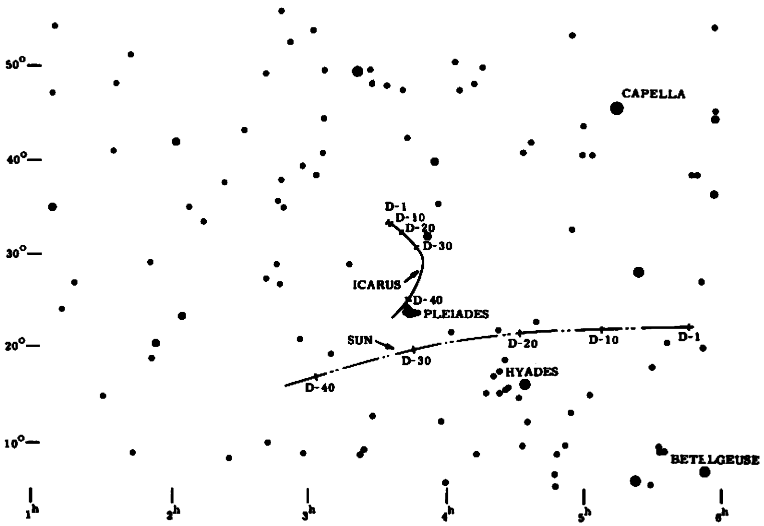


1.5
Visual magnitude of Icarus (from 12 hr to collision)

during this period, 18th to 19th magnitude, Icarus can be detected only with the largest telescopes, it begins to become visible to the naked eye at about 5th or 6th magnitude, less than 9 hr before collision (fig. 1.5).

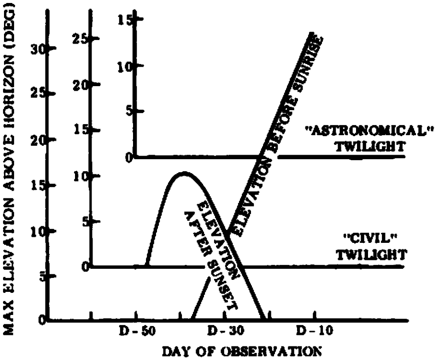
If the sun did not obscure the star field behind it, the trace of the hypothetical orbit of Icarus and of the sun's apparent path on the celestial sphere would be as shown in fig. 1.6. From D-1 (1 day before collision) until impact (D) Icarus would appear as a brightening point on the celestial sphere. Such a view is most easily obtained outside the earth's atmosphere, where diffusion of sunlight is minimized. Although the proximity of lines of sight to Icarus and to the sun from just outside the earth's atmosphere hampers observation of the asteroid, nevertheless, observation by a star tracker is possible with a suitable sun shield (see section on electro-optical instrumentation, p. 79).

Within the atmosphere, optical telescopes are severely restricted. Since Icarus remains extremely dim until a few days before collision, even the largest ground-based telescopes require a relatively dark background, that is, after



1.6
Apparent path of Icarus across the heavens (hypothetical orbit)

sunset, to insure observation. The proximity of Icarus to the sun causes Icarus to be, at most, low in the sky when the sun is over the horizon. Its elevation is then reduced approximately 15°/hr after sunset or before sunrise. Observation periods, if available at all, are thus very short. Figure 1.7 shows the maximum elevation achieved by Icarus during the last 50 days before impact. "Civil" twilight is the beginning of "night" for legal purposes, while "astronomical" twilight is the condition of near-maximum darkness. By waiting for astronomical twilight, a necessary condition for observation, one must look for Icarus near the horizon, where city lights and the thickest portion of the atmosphere hamper viewing and where most large telescopes will not even operate. Despite the difficult visibility problem, every attempt to track Icarus during the last few days before collision must be made in order to pinpoint its trajectory as accurately as possible.



1.7
Elevation of Icarus

Physical Characteristics of Icarus

Although Icarus is commonly called an "asteroid," its origin is in fact a subject of considerable debate. If Icarus is an asteroid, its eccentric orbit can be explained as the result of a perturbation by other heavenly bodies. But according to Opik (2, 3) those "asteroids" whose orbits are considerably different from those of the bodies in the asteroid belt may have a cometary origin. That is, Icarus may in fact be a dead cometary nucleus consisting of a conglomerate of ice, dust, and gases. A number of other theories exist concerning the origin of Icarus, each theory implying a different set of physical characteristics for the body. The theory of cometary origin, for instance, suggests a relatively low density, while a true asteroidal origin implies the density of stone or iron.

To insure a conservative mission plan, that is, a "worst-case design," for Project Icarus, bounds on the physical characteristics of the body were determined from existing data and theories. First, the albedo or reflectivity of Icarus was established between 0.07 and 0.28, approximately that of the moon and of the large asteroid Vesta, respectively (4). Together with observed brightness measurements, the albedo is sufficient to indicate the limits of the radius of a spherical Icarus (5): 1300 to 2500 ft. The most commonly used value for albedo yields a most-probable radius of 2100 ft.

According to Whipple, the density of Icarus is between 1.3 g/cm^3 and 8.0 g/cm^3 (4). The weight of Icarus is then between 380 megatons (Mt) and 17,000 Mt, although the most probable density, 3.5 g/cm^3, together with the 2100-ft radius, yields a nominal weight of 4400 Mt.

The rate of rotation of an asteroid and the axis of its rotation can be found approximately by careful analysis of the shape and variation of its light curve, a tabulation of the brightness of the asteroid as it varies with time. In general the period of rotation can be found during 1 long night of observation, or over a period of 2 or 3 consecutive nights (6).

The shortest period of rotation of an asteroid determined to date is 4 hr, 9 min. The longest period is about 18 hr. According to Ahmad, the theoretical limit of rotational period is 3.3 hr for an asteroid of density 3.5 g/cm^3 (7). This limit, calculated from Jeans (8), is valid for an incompressible fluid, and thus accounts only for the gravitational attraction of the fluid particles. If one considers also the tensile strength of particles in a stony or iron asteroid, the rate of rotation can increase considerably, perhaps to as high as 1 rpm, without breaking up the asteroid. For purposes of narrowing the detection bandwidth of the radar used to track Icarus, it is most appropriate to consider Icarus' rotational rate as the fastest that has been observed to date. Telescopic observations of Icarus as it approaches the earth may afford more precise information about the true rotational rate.

According to Groereveld and Kuiper, very little can be said about the shape or axis of rotation of an asteroid until it has been observed on at least 4 epochs during 2 oppositions, preferably near the stationary points (6). The high eccentricity of Icarus' orbit makes such observations a near impossibility. Only the shapes of the largest asteroids can be observed as more than points with the world's largest telescopes. Such observations have indicated both irregular, elongated shapes and nearly perfect disks. One might even postulate a doughnut shape for Icarus, similar to that of the iron meteorite of Tuscon, Arizona. Because of its relatively small size, the shape of Icarus will remain its most uncertain characteristic.

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