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Close Encounters of Asteroids and Comets to Planets

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NATIONAL LABORATORY

Close Encounters of Asteroids and Comets to Planets

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Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). We find by numerical simulations that the elongated-potato shape that is characteristic of Earth-crossing asteroids (ECAs) is likely the result of previous close tidal encounters with Earth. Some meteoroids graze the atmosphere of Earth before returning to space (at reduced speed). We used a spherical atmospheric model to study such grazers to find the condition under which they are captured into gravitationally bound orbits around Earth. We find that for about every thousand iron asteroids that hit the Earth, one is captured into a gravitational-bound orbit. Some fraction of these captured objects will have their orbits stabilized for many revolutions by tidal encounters with the Moon and the sun. We have also studied how the damage produced by such grazing and near-grazing asteroids differs from that produced by asteroids that hit Earth more directly.

Background and Research Objectives

Even after 4.6 billion years, the dynamical evolution of the solar system is not over. Perturbations by passing stars bring new comets into the planetary system from the distant solar comet cloud. Perturbations by the outer planets nudge short-period comets into the inner planetary system from the Kuiper belt, a band of comets just beyond Neptune. Collisions within the asteroid belt perturb some asteroids into resonant orbits with Jupiter, which, in turn, perturbs them into orbits that cross the orbits of Mars and Earth.

Asteroids and comets in Earth-crossing orbits eventually impact the planet or are forced into hyperbolic escape orbits away from the sun by close encounters with Earth. When they impact Earth, they produce damage that range from the extinction of the dinosaurs and the production of a 200-km diameter crater by an impactor that hit the Yucation 65 million years ago, to the flattening of 2000 square kilometers of forest by a 70-meter-diameter asteroid that impacted near Tunguska River, Siberia in 1908.

The direct collision of a comet or asteroid with a planet is spectacular, but more distant encounters are more common and can have major effects on the orbits and even the structures of these objects. We have looked at the tidal effect of the Earth on asteroids during such close encounters and the effect of its atmosphere on asteroids during close or grazing encounters.

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The tidal perturbations by the planets on comets and asteroids may be responsible for a number of observed features of the Earth-crossing asteroids. Some of the features that we investigated include:

1. Earth-crossing asteroids including Castalia and Toutatis that have been imaged by Earth radar resemble two pears bound together at their narrow ends. Asteroids are believed to be highly fractured due to collisions in the asteroid belt. Hills and Leonard (1995) conjectured that that this shape may be due to these objects having made close approaches to Earth (which is highly probable) during which the tidal field pulled apart the constituents of the asteroid into the observed elongated structures.

2. About 10% of the large craters on Earth are double. The only reasonable explanation appears to be double asteroids. How did they form? We believed that these double asteroids may have formed by tidal encounters that were stronger than those that produced the pear-shaped asteroids, but not strong enough to tidally break up these objects.

3. The Spacewatch telescope at the University of Arizona has observed a large enhancement in the number of Earth-crossing asteroids with diameters in the range of 1 to 100 meters. These objects have relatively low velocities with respect to Earth. We believed that they are tidal debris of objects that have passed close to Earth. Low-velocity objects would suffer more tidal damage at a given closest approach to Earth than those with higher velocities.

We believed that the research on tidal encounters would allow us to better determine how they may increase the asteroid impact hazard. We also wanted to see how practical it was to capture asteroids into Earth orbit. Such captured asteroids could provide the raw materials needed to allow a much-expanded technology in Earth orbit.

Importance to LANL's Science and Technology Base and National R&D Needs

It has become recognized by the public and Congress that asteroid and comet impacts are a grave threat that will have to be addressed before a devastating impact occurs. The DOE's role in this effort was recognized as early as 1992 when the second of two meetings mandated by Congress to look into the impact threat and its mitigation was held at Los Alamos. This meeting led to some Los Alamos representatives testifying before Congress on this issue. Every international and national meeting on the asteroid threat and its mitigation has requested participation by Los Alamos scientists. They have responded and they have continued to make steady progress in understanding the threat and the steps required for its mitigation.

This work has been recognized as contributing to the Laboratory's effort in threat reduction. The DOE, NASA, and DoD are the principal agencies working on the impact threat. NASA, which is chartered to do space exploration and engineering but not threat reduction, has contributed by sending space craft to look at Earth-crossing asteroids. It has also paid for some searches for Near-Earth objects from the ground. DoD has contributed (in its role of "knowing the enemy") by allowing some of its satellite tracking stations to be used to search for Earth-crossing asteroids. The DoD asteroid discovery programs have become much more effective than the programs supported by NASA. The DoD has also used its space surveillance satellites to observe the breakup of larger meteors (small asteroids) in the atmosphere. It also began the construction of an interplanetary spacecraft (Clementine II) that would have intercepted several asteroids and hit them with projectiles. This exercise would have provided scientific knowledge of the strength of asteroids, which is needed before we can deflect them from Earth impact. It also would have given DoD the beginning of a capability to project strength against an asteroid to deflect it or break it up.

The DOE, with its role in threat reduction, plays a pivotal role between NASA, which is primarily concerned with gathering knowledge about these objects, and DoD, which ultimately would provide the force to deflect them. LANL, as a DOE laboratory concerned with threat reduction, has concentrated on understanding how much damage these objects can do so their threat can be prioritized against other national threats. It has also devised methods to deflect and break up these threatening objects. DoD will ultimately be responsible for applying these methods against the asteroids.

This work continues the tradition of DOE-LANL contribution to this field. It adds to the Los Alamos expertise in computer modeling and in space science. By the more precise modeling of the properties of large meteors passing through the atmosphere, this work helps clarify the nature of objects that in some ways, such as total energy release, mimic that of a nuclear weapon in the atmosphere.

Scientific Approach and Accomplishments

There are three major areas of accomplishment and three major refereed papers that came out of this study. In chronological order they include the tidal deformation of asteroids passing near Earth (Solem and Hills (1996), the capture of asteroids in Earth Orbit (Hills and Goda 1997), and damage expected from asteroids hitting at close to grazing collisions (Hills and Goda 1998). We shall consider each of them in turn.

The Shaping of Earth-Crossing Asteroids by Tidal Forces

Three closely investigated near-earth asteroids, Castalia, Toutatis and Geographos, exhibit a characteristic elongated "potato" shape when viewed with Earth-based radar. We investigated the conjecture (Hills and Leonard 1995) that this shape may be characteristic of a close tidal encounter of these asteroids to the Earth or other planets.

The population of Earth-crossing asteroids (ECAs) is approximately in a steady state such that the number being removed from it by Earth collision is balanced by a similar number entering it from the asteroid belt. For every object that hits Earth, another 3 pass within 2 Earth radii of its center without hitting it (ignoring gravitational focusing, which is relatively small at typical asteroid impact velocities), so a sizable fraction of the current ECA population has passed near Earth.

We addressed the tidal distortion problem by calculating a series of test encounters with Earth, modeling each asteroid as an assemblage of rocks bound together only by their mutual gravitation. This model is consistent with the modern view of asteroids and comets as "rubble piles". This structure is expected from the fracturing of the asteroids in collisions within the asteroid belt.

We modeled the test asteroids as conglomerations of 135 identical, individually competent spherical rocks bound together only by their mutual gravitation. This simplification is necessary at this stage of analysis. The actual asteroid components are not all spherical and they may have cohesive forces between them, but we assume these forces are much smaller than gravity. The components of a model asteroid interact only by gravity except when they touch. The collision of two components is treated as a non-adhesive frictionless scattering, i.e., the velocities are changed instantaneously in such a way that linear momentum is conserved, but some of the kinetic energy may be converted to heat. Because the spheres are frictionless, they receive no spin in a collision. The simulation is a detailed calculation of the gravitational interaction and collisions of the components --- it is not a hydrodynamic calculation.

A further simplification that greatly speeds computation is the assumption that radius and density of each component is the same. Given our present state of knowledge (or ignorance), it would be presumptuous to specify exactly how the components lose kinetic energy in collisions. We assume that they thermalize about half their relative kinetic energy in an average collision.

To model the pre-encounter asteroid, we place one of its components at the center of mass, COM, with its fellow components packed around it in a face-centered cubic (FCC) array, which results in a model rubble-pile asteroid in which the components are close to a gravitational potential minimum.

The model has a remarkable scaling relationship: if we increase the diameter of the asteroid by a factor of 2 and keep the same number of components, the geometrical arrangement of all components at any time during the encounter will be exactly the same, but with the distance between them increased by a factor of 2.

The energetics enjoy a similarly simple scaling. A factor of 2 increase in the radius of each component (while keeping its density constant) increases all energies (kinetic energy, gravitational potential energy, and thermal energy generated in component collisions) by a factor of $2^5=32$. As a result of these scalings, we can treat asteroids of all sizes with a single calculation if all other encounter parameters are the same. The only intrinsic parameters of the model asteroid that we can vary are: (1) its density, (2) number of components in the asteroid, and (3) the elasticity of these components when they collide with each other. We have found that only density is important.

The general scenario found in our simulation of a tidal encounter is as follows. The tidal forces knead the asteroid and do work on the asteroid as it passes by Earth. At early stages, the work produces agitation of the components, which raises their net kinetic energy with respect to the COM. The global flow velocities generated by the tidal field eventually distort the asteroid, which raises (makes less negative) its net gravitational potential energy (which decreases its binding energy). At later stages, collisions among the components of the asteroid convert the net kinetic energy into heat. When the asteroid moves away from the planet, the self-gravitation of its components begins to regain dominance over the tidal force (unless the asteroid has gained enough tidal energy to become dissociated), so the distorted asteroid relaxes to a more compact state. The net internal kinetic energy of the pieces due to their motion relative to the COM of the asteroid is converted to heat as the chunks collide and the net potential energy decreases (becomes more negative).

We find that the distortion induced in a tidal encounter increases as the asteroid approach velocity and its closest approach distance to Earth decrease. We find some cases where the ratio of long to short axis after the encounter exceeds 3.5, which is significantly larger than that found for any observed Earth-crossing asteroid. The tidal explanation does, indeed, seem adequate to explain the observed distortion of these objects. Geographos, which has the largest known elongation of $E = 2.7$, is difficult to explain as a collisional fragment, but the tidal model works well. However, our models of tidally deformed asteroids appear more symmetric than the observed asteroids (except perhaps for Geographos). This is not surprising since all of our model constituents have equal masses. If the constituents of the asteroid are of unequal size and shape, the tidally distorted asteroids might more closely resemble the observed objects. We conclude that the observed appearance of the elongated ECAs is consistent with their being formed by tidal deformation.

Due to the high elongation, E = 3.5, of our model asteroid after a near-grazing collision at an impact velocity of 15 km/s, we believe that if the impact velocity is a little less than this value, the asteroid would be dissociated in the encounter. We have considered an encounter in which the impact velocity at closest approach is just that expected for a parabolic encounter (about 11.2 km/s). We find that such an encounter would totally disrupt rubble-pile asteroids with densities of 3.4 g/cm^3.

The tidal encounters cause the asteroids to rotate. In close encounters and low velocities, they are rotating near their maximum stable values. If they rotated faster, they would fly apart. We expect that detailed examination of parameter space near where we found the maximum rotation would show the formation of binary asteroids. Such binary asteroids could explain the formation of double craters on Earth.

Any initial rotation or elongation of the asteroid would make it more vulnerable to further elongation or breakup compared to that of the nonrotating, spherical asteroid used as the initial state in our simulations. These considerations suggest the need for more work, but they also indicate that the maximum tidal distortions are likely to be even larger than calculated by our simple models.

The lower the velocity of an asteroid with respect to Earth, the more tidal deformation it suffers and the easier it is to pull it apart. The fact that asteroids that have low velocities with respect to Earth are more easily torn apart in a tidal encounter may explain the over abundance of small asteroids (peaking at diameters of about 10 meters) having low velocities with respect to Earth that have been detected by the Spacewatch telescope.

Capturing Asteroids into Earth Orbits by Grazing Atmospheric Encounters

While meteoroids that graze the atmosphere of Earth are rare, they can produce spectacular meteors that are witnessed by a large number of people due to the long time they spend in the atmosphere. Examples of such meteors include that of August 10, 1972, that went over the western United States and Canada, the European fireball of October 13, 1990, and the October 1992 Peekskill grazer that traveled north over the eastern United States. The first two grazers returned to space after losing some kinetic energy in the atmosphere. The third one lost enough kinetic energy that it plunged to Earth. A fragment of it hit a parked car in New York State. An even more interesting grazer appeared over New Mexico and Texas, in the Southwestern United States, on the evening of October 3, 1996. It may have returned to space over Texas and then reentered the atmosphere in California 100 minutes later.

We used a spherical atmospheric model to integrate the passage of meteoroids in grazing atmospheric encounters. Such a model has not been used before to study meteoroid encounters with the atmosphere. We examined the dynamics of grazing meteoroids. In particular, we found the range of closest approach distances in which the objects are captured into bound orbits around Earth. This allowed us to determine the rate at which meteoroids of various types and impact velocities are captured into temporarily bound orbits. Some of these captured objects with large enough semi-major axes could be hurled into longer lived orbits by lunar and solar perturbations or by technological intervention.

To study the dynamics of the grazers, we modified the meteor code used by Hills and Goda (1993). In that paper, we studied the fragmentation of small asteroids in the atmosphere in order to determine the damage they do as a function of their mass, composition, and impact velocity. Our original computer model used a plane parallel atmosphere into which the meteoroids entered from the zenith. The atmospheric density as a function of height was assumed to be exponential with a constant scale height. In the current paper, we improve upon the original model by using a spherical atmosphere in which we find the density as a function of height by fitting a curve to the data in the Standard Atmospheric Model. These refinements allow us to consider meteoroids that enter at large zenith angles and to improve the results for objects that suffer large energy dissipation at high altitudes.

Fragmentation enormously increases the atmospheric drag on a meteoroid, so it dissipates much more of its energy in the atmosphere. In this paper we use the atmospheric fragmentation model proposed by Hills and Goda (1993). It quantitatively reproduces many of the observed properties of meteoroids that are large enough to undergo nearly continuos fragmentation over some fraction of their atmospheric passage.

The long path lengths in the atmosphere make these calculations long and expensive. In addition, there are many initial parameters: meteoroid type, radius, impact velocity, and impact parameter. There are a number of output parameters of interest. The large parameter space makes it difficult to do a comprehensive study. We can only give an overview of the problem.

Meteoroids that graze the atmosphere of Earth spend much more time in it than if they entered it at a small zenith angle. Figure 1 shows the path lengths of meteoroids within the atmosphere in the absence of energy dissipation as a function of their closest approach distance, h_{min}, to the surface of Earth. The top of the atmosphere is defined to be the 100-km elevation level. The calculations are made for several values of the impact velocity at infinity. They allow for gravitational focusing. The lower the impact velocity, the more the orbit is bent by the gravitational attraction of Earth, which forces the meteoroid to spend more time within the atmosphere. We note that the maximum arc length in the atmosphere for the closest possible approach to the surface of Earth h_{min} is over 2000 km at all the calculated impact velocities and over 3000 km for the lowest ones.

Figure 2 shows how atmospheric dissipation modifies Figure 1. It gives the distance traveled in the atmosphere by iron meteoroids as a function of their theoretical closest approach distance, h_{min}, for meteoroid radii R = 1, 5, 10, and 20 meters. The calculations at each radius are made for velocities at infinity, $V_\infty = 2, 5, 10, 15$, and 20 km/s. At small h_{min}, the distance traveled in the atmosphere is much less than it would be without dissipation (as given by Figure 1). The atmosphere quickly stops these objects so they plunge to ground. At large values of h_{min}, Figure 2 fits Figure 1 well because atmospheric dissipation is low. At intermediate values of h_{min}, the arc length can be much larger than given by Figure 1. Here the object dissipates enough energy for its orbit to become nearly circular before it returns to space or plunges to ground. Objects that have h_{min} a little higher than those producing the peaks in Figure2 have the highest probability of being captured into bound orbits around Earth. Figure 2 shows that the larger the radius R of an iron meteoroid, the smaller the value of h_{min} needed to circularize its orbit. Stony meteoroids show similar behavior except they have lower densities and they tend to fragment at small values of h_{min}, so they are more easily stopped by the atmosphere than iron meteoroids of the same radius.

Figure 3 shows the semi-major axes, a, of the orbits of the captured meteoroids as a function of h_{min} for those with $a > R_\oplus$. They should increase towards infinity at the largest h_{min} that allows capture. That this approach to infinity is not shown in the figure is due to our using only 1-km resolution in h_{min}. We see again that the range of h_{min} that allows capture is large at small values of V_∞ but decreases as V_∞ increases. The figures for different values of meteoroid radius R look similar, but they are shifted towards smaller values of h_{min} as R increases. This similarity of appearance results from the irons not usually fragmenting at these low velocities and from the approximate constancy of the scale height as a function of atmospheric height. We note that a small fraction of the semi-major axes exceed 10 km or 150 $R_\oplus$, which makes their orbits highly susceptible to solar and lunar perturbations. Objects in these large semi-major orbits have the best chance of being perturbed into bound, long-lived orbits.

Figure 4 and Figure 5 show the range of h_{min} and V_∞ in which irons and stones, respectively, are captured into bound orbits (with semi-major axes greater than 1 $R_\oplus$) in an atmospheric encounter. We again note that the zone permitting capture narrows with increasing impact velocity. The triple points in the curves for large stones result from fragmentation, which greatly increases the atmospheric drag. The small stones are slowed enough high in the atmosphere that they do not fragment in grazing collisions, so they produce no triple points. The larger ones fragment if their impact velocity exceeds a given value that is determined by h_{min}. The fragmentation increases the drag enough so objects that would otherwise be captured into bound orbits or escape are now trapped by the atmosphere. Fragmentation causes the turn up in the curves in Figure 5 at large impact velocities. The higher the impact velocity, the larger h_{min} must be so there is no early fragmentation that would cause a catastrophic loss of kinetic energy in the atmosphere and prevent the object from returning to space.

From the data in Figure 4 and 5, we can determine the ratio of the number of objects captured into bound orbits in grazing atmospheric encounters to the total number that (eventually) hits Earth. Figure 6 and 7 show the computed fraction of objects captured for irons and stones respectively. The probability of capture drops rapidly with increasing V_∞ but it is about 0.1 for irons at typical impact velocities. It disappears altogether for larger stones at high impact velocities because of their fragmentation.

While only about one meteoroid in a thousand that impacts Earth is captured into a bound orbit with a semi-major axis greater than 1 $R_\oplus$, the meteors associated with such grazing collisions are visible over a much larger fraction of Earth than those that hit the atmosphere more directly. Captured objects constitute a much larger fraction of *observed*, bright meteors than this value suggests. As evident from Figure 3, the median semi-major axis of such captured meteoroids is several Earth radii at low impact velocities. Most of these objects plunge to the ground on their second trip through the atmosphere, as did the October 3, 1996, grazer. Some small fraction (which needs to be determined) of the captured meteoroids have sufficiently large semi-major axes that perturbations by the sun and moon near their orbital apogees will raise their perigees above the atmosphere. These can make several orbits around the Earth before they are perturbed into an orbit that causes them to impact Earth or the moon or be ejected from the Earth-moon system.

Effect of Zenith Angle on the Damage Expected from Small Asteroids

Hills and Goda (1993) studied the fragmentation of small asteroids in the atmosphere to determine how much damage they do as function of their mass and composition. The model was limited to a plane parallel atmosphere into which the impactors enter from the zenith. The atmospheric density as a function of height was assumed exponential with a constant scale height. We improve the model by using a spherical atmosphere in which the atmospheric density as a function of height is found by fitting a curve to the United States. Standard Atmospheric Model. These refinements allow us to consider impactors that enter at large zenith angles and to improve the results for impactors that suffer large energy dissipation high in the atmosphere. The papers of Hills and Goda (1998) give very detailed analysis of the results. We will only treat some of the highlights here.

Even if all of the meteoroid energy is dissipated in the atmosphere, it can produce blast-wave damage. If they are small enough, they dissipate their energy sufficiently high in the atmosphere that they produce no blast damage. We find that the blast waves from soft stony meteorites, which constitute most of the meteoroids, only cause ground damage if their radii exceed about 22 meters at zero zenith angle. At zenith angle 60°, the minimum radius is about 28 meters. The corresponding kinetic energies for these two bodies are 5 megatons and 10 megatons. Smaller stony asteroids break up too high in the atmosphere to produce any blast damage at 4 p.s.i. overpressure. The radius of destruction increases rapidly with increasing asteroid radius. It reaches an area of 2000 sq. km, the size of the Tunguska blast of 1908, at a radius of 35 m at zenith angle 0 and a radius of about 40 m at 60°. This would be the required radius of the Tunguska impactor if its knocking down the forest required an overpressure of 4 p.s.i. If the 4 p.s.i. overpressure was only reached over 1000-km^2 at Tunguska, the radius of the impactor would drop to 30 meters at zenith angle 0 and to about 35 meters at 60°. The corresponding impact energies would be 13 and 20 megatons. The lower figure is close to the energies estimated by Shoemaker from microbaragraphic measurements.

If an asteroid is large enough, the atmosphere is not able to dissipate all its kinetic energy, so it can produce ground impact damage: craters, tsunami, and earthquakes. Figure 8 shows the fraction of the initial kinetic energy of the impactor that goes into ground impact. These results allow for ablation. We see from the figure that for soft stones ground-impact damage is not important unless the radius of the object exceeds 80 meters at zero zenith angle and about 150 meters at 60°. Near-grazing encounters at zenith angles 80° and 81° allow most of the energy to be dissipated in the atmosphere for objects up to 1 km in radius. For irons, ground impact damage is not important unless the radius exceeds about 10 meters while for comets the minimum radius is about 500 meters. The paper by Hills and Goda (1998) gives much more detail.

We have found that the atmosphere is ineffective in preventing impact damage to the ground at zenith angles less than 60° when the radius of a stony asteroid exceeds 100 meters and that of a comet exceeds 500 meters. For iron meteorites the critical radius is about 30 meters at a moderate impact velocity. While the dissipation of energy in the atmosphere protects the ground from impact damage (craters, earthquakes, and tsunami), it can enhance the damage done by the airburst. Near grazing collisions can cause stony asteroids as large as 2 km in diameter to lose most of their energy in the atmosphere.

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[2] Hills, J.G. and Leonard, P.J.T, "Near-Earth Asteroids: The Last Days before Earth Impact", Astronomical J., **109**, 401-417, 1995.

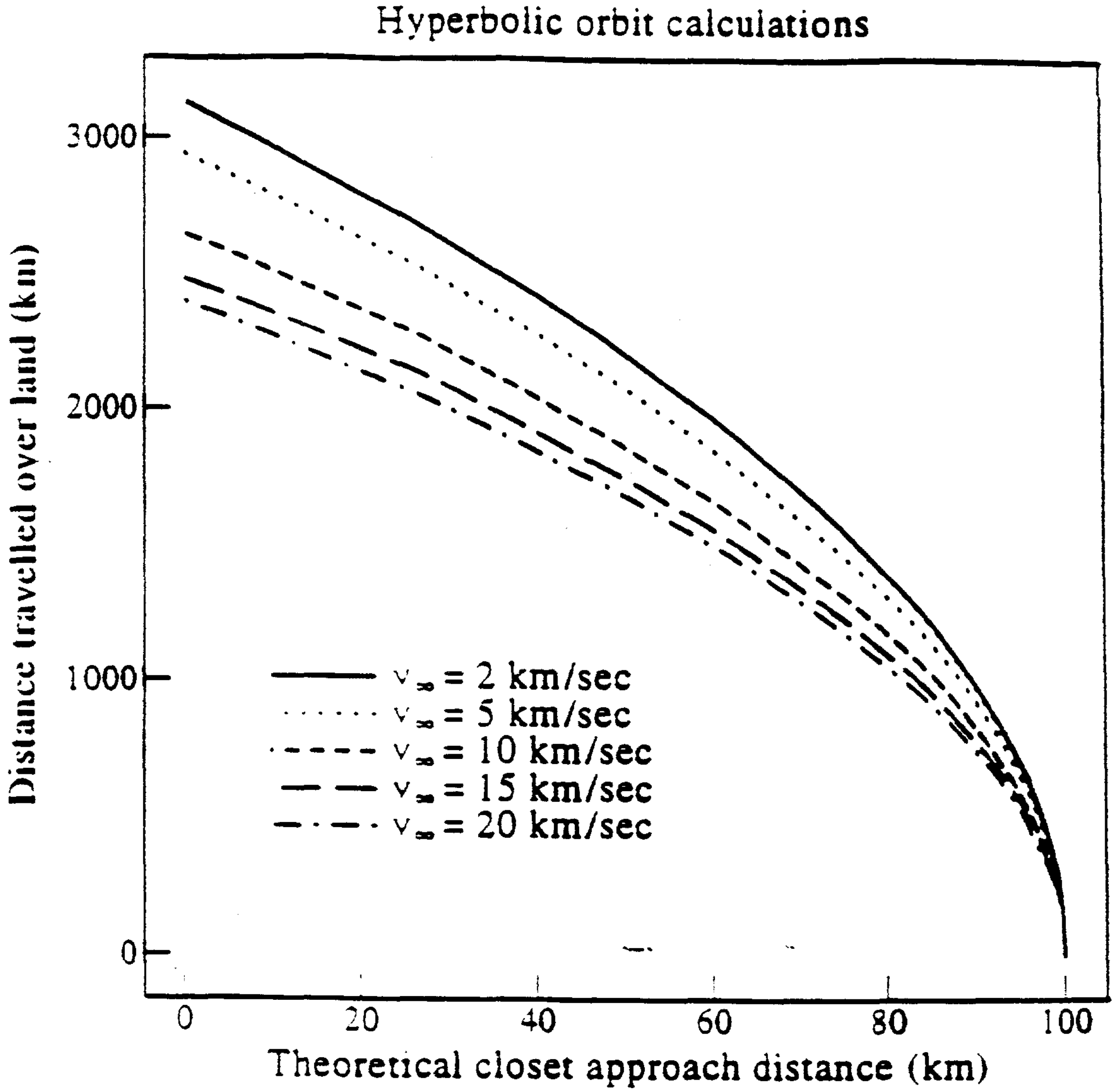

Figure 1: The length of arc through the atmosphere of a grazing meteor in the absence of atmospheric dissipation. The length is given as a function of the closest approach distance to the surface of Earth for various values of the impact velocity at infinity. The atmosphere is assumed to terminate at a height of 100 km.

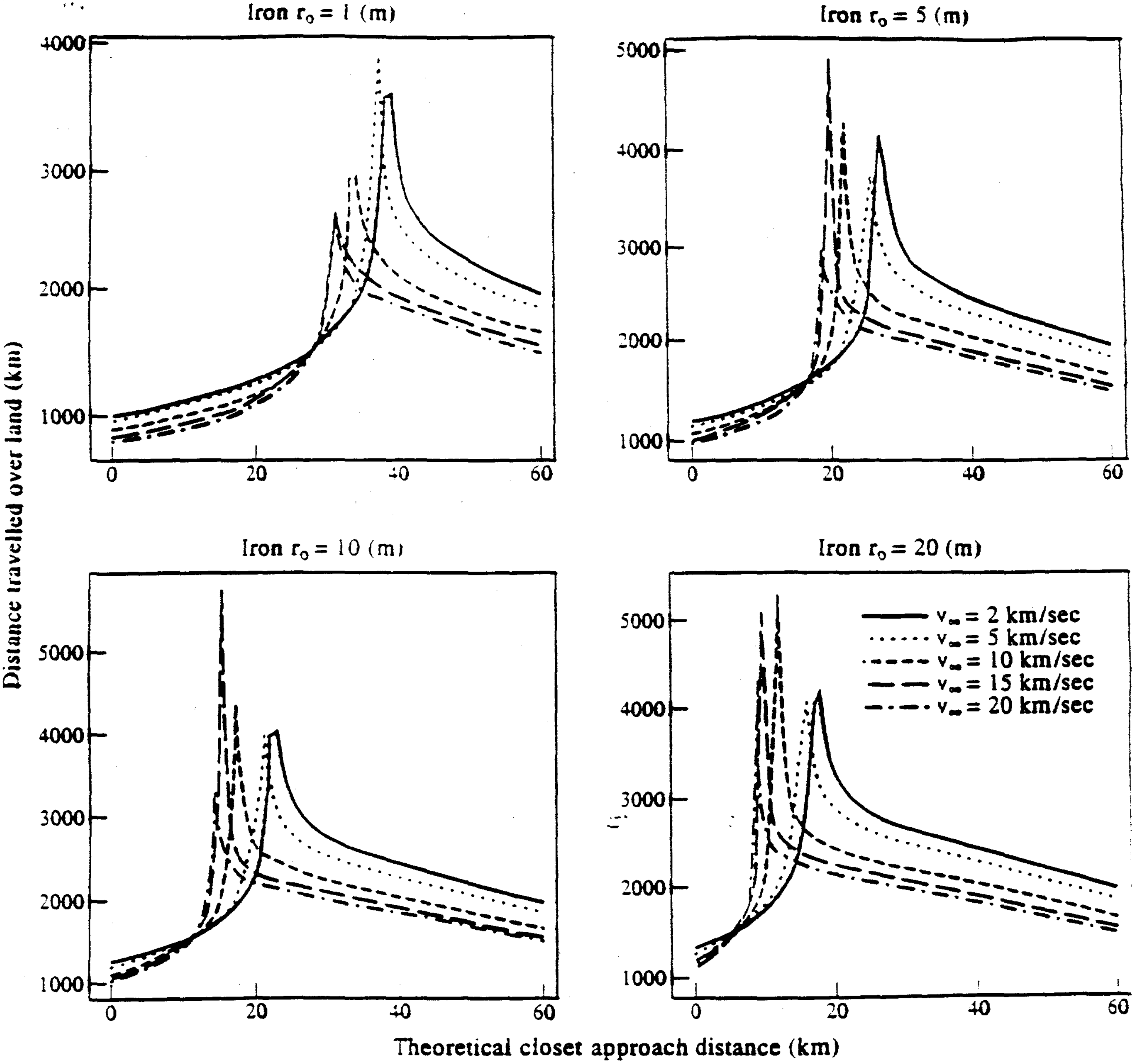

Figure 2: The length of arc of a grazing iron meteoroid allowing for atmospheric dissipation. This is given as a function of the projected closed approach distance to Earth in the absence of atmosphere dissipation. This is computed for meteoroids with radii of 1,5,10, and 20 meters. For each radius, it is computed for impact velocities at infinity of 2,5,10,15, and 20 km/s.

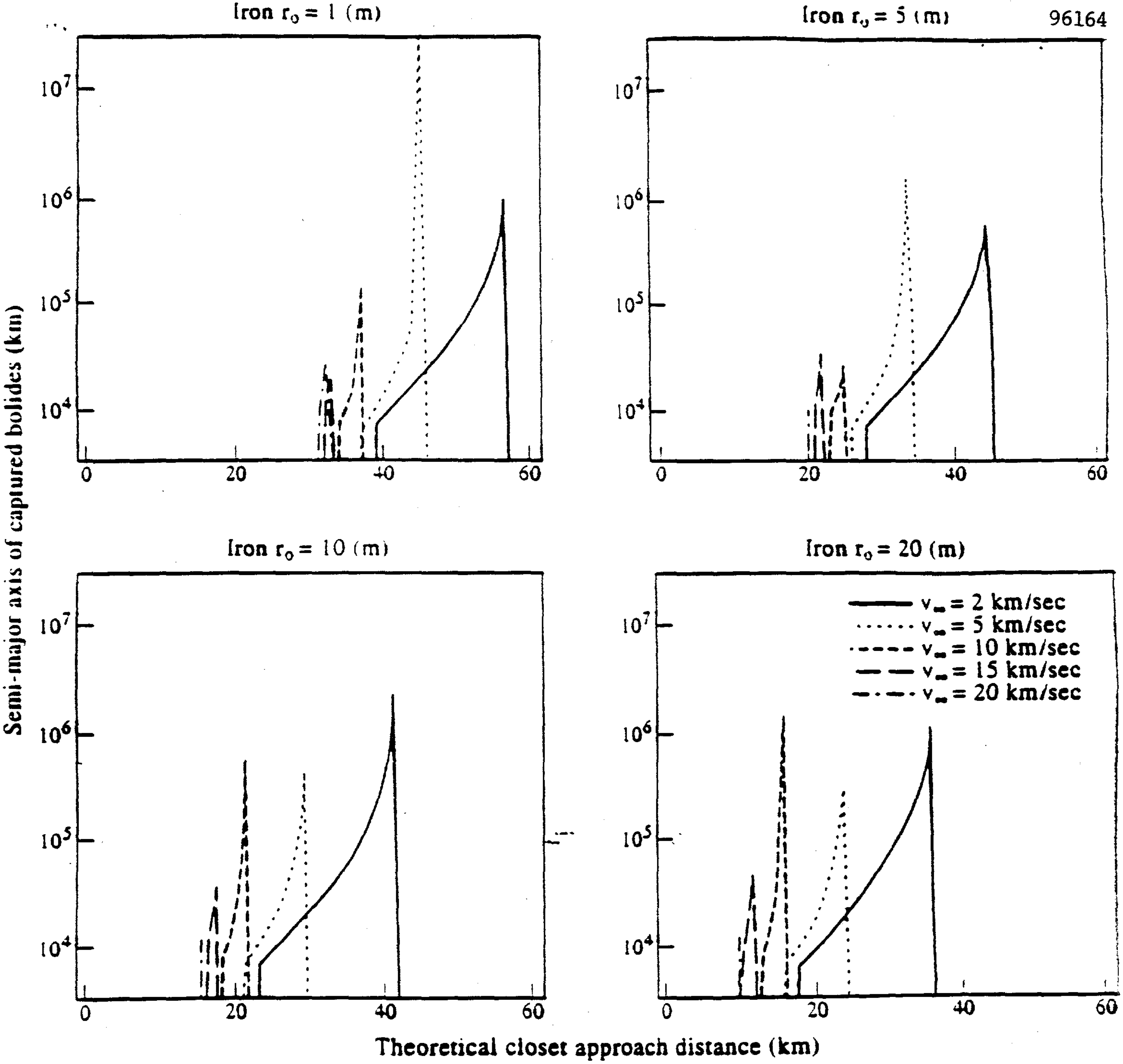

Figure 3: Semi-major axes of captured iron bolides. This is shown for meteoroids of radius 1, 5, 10, and 20 meters for impact velocities at infinity of 2, 5, 10, 15, and 20 km/s. We only consider semi-major axes greater than 1 Earth radius.

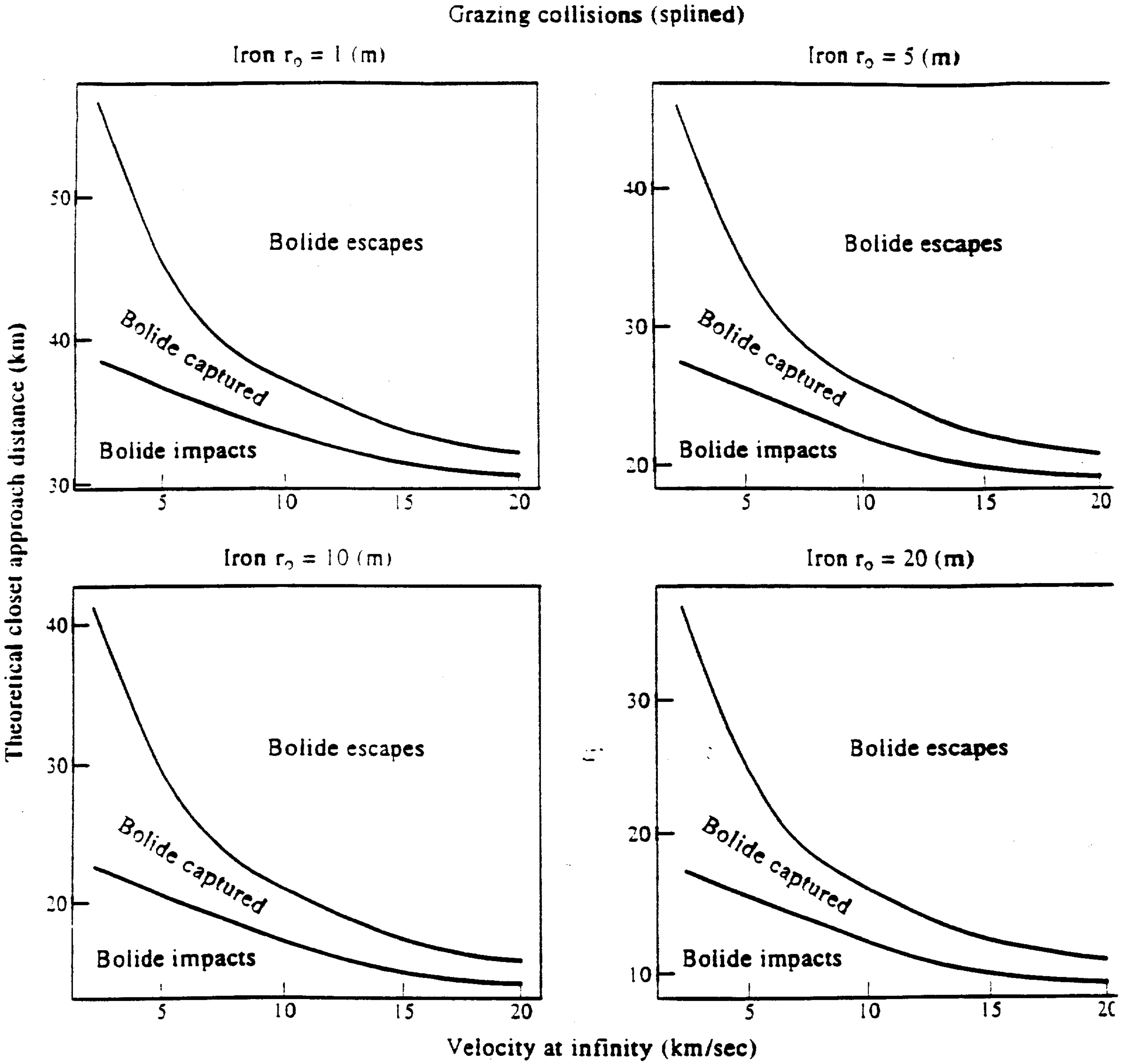

Figure 4: The region of parameter space in which iron meteoroids are captured into bound orbits about Earth with semi-major axes greater or equal to 1 Earth radius. This is given as a function of the projected closest approach distance of the meteoroid to Earth (in the absence of atmospheric dissipation) and the impact velocity at infinity.

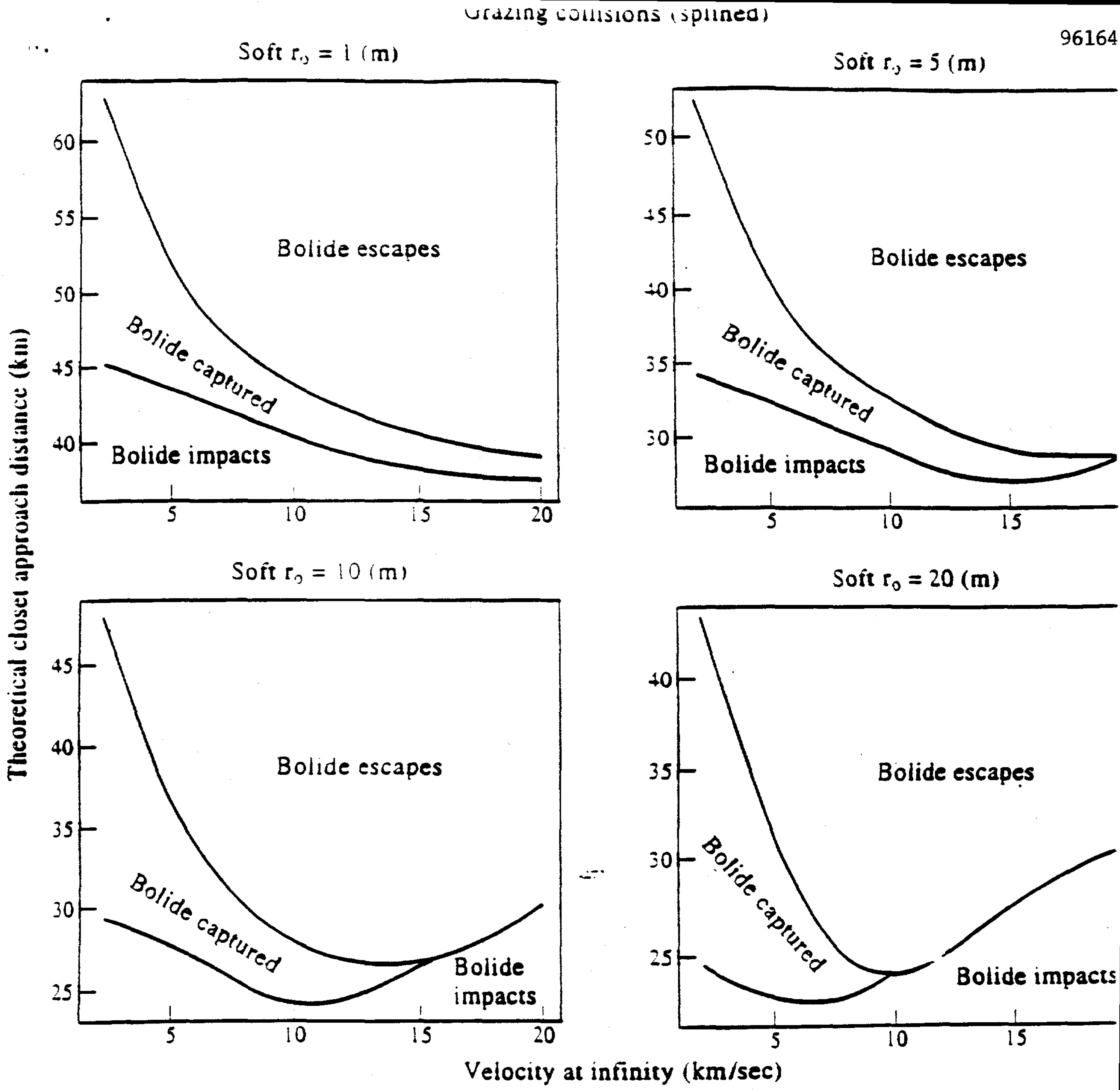

Figure 5: Same as Fig. 4 except that it is for stony meteoroids.

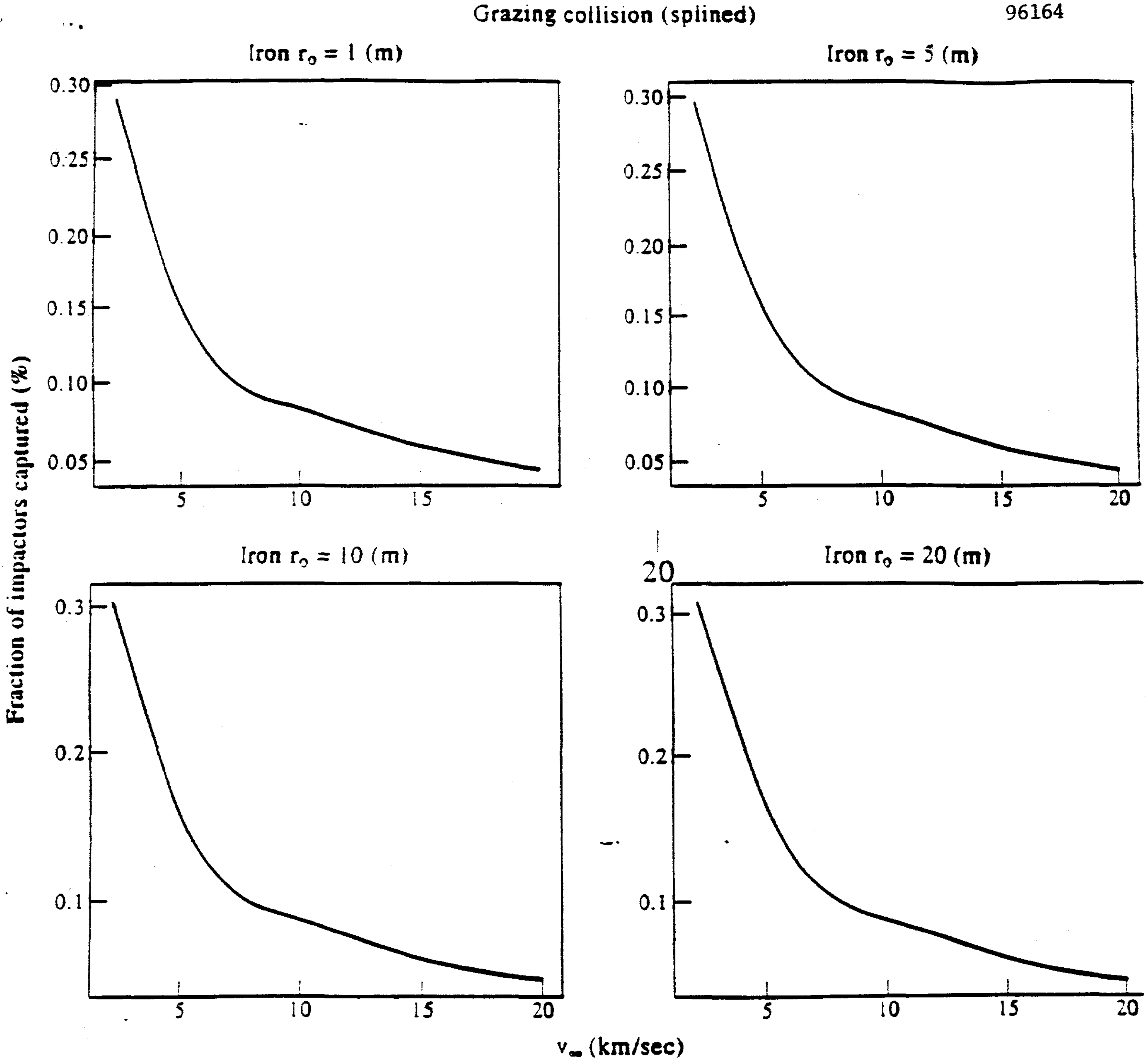

Figure 6: Fraction of iron meteoroids encountering Earth that are captured into bound orbits with semi-major axes greater than 1 Earth radius. The remainder either hit Earth after the initial passage through the atmosphere or if they leave its atmosphere they reenter it after going less than one orbit around Earth.

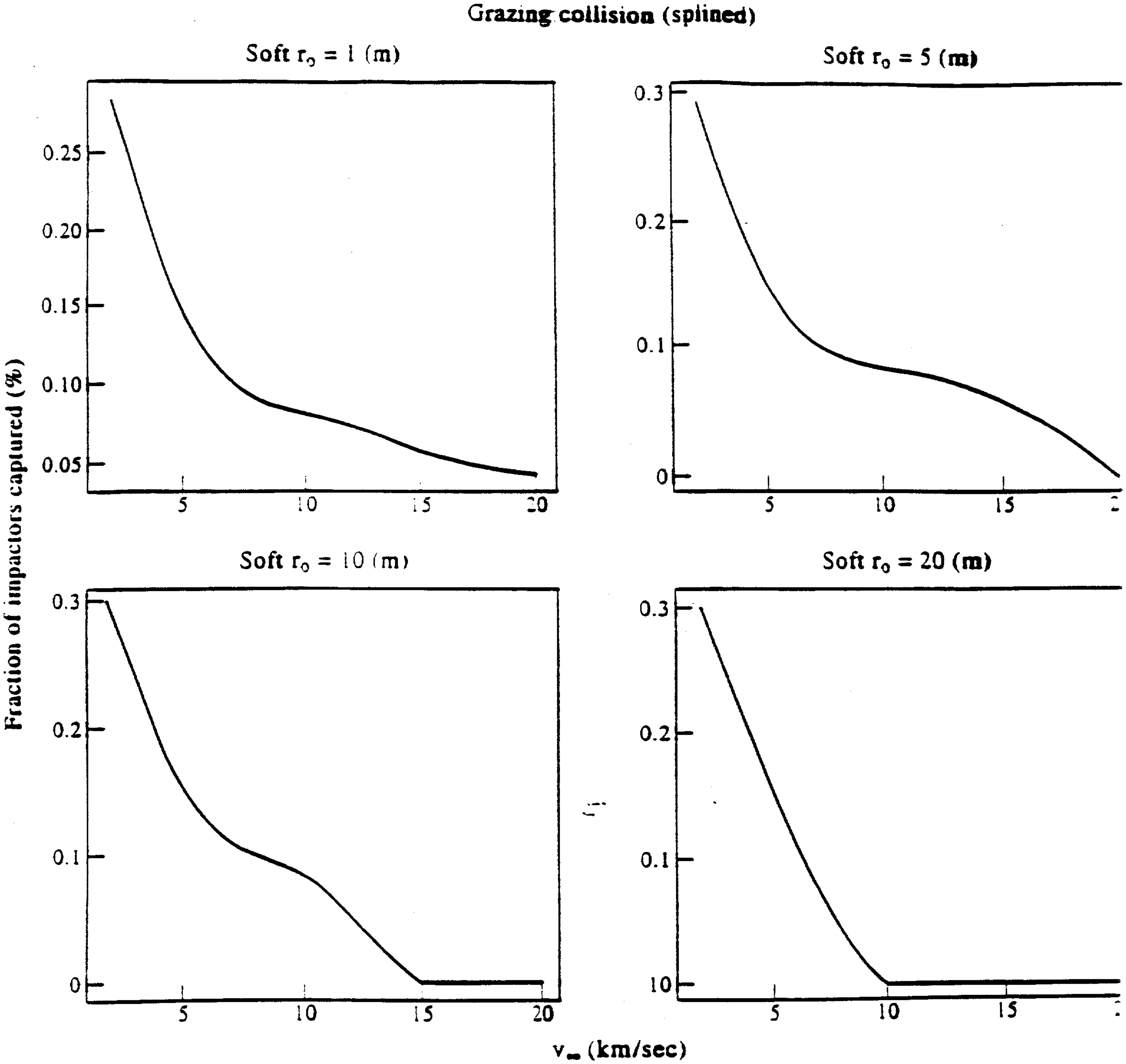

Figure 7: Same as Fig.6 except that it is for stony meteoroids.

FIGURE 8

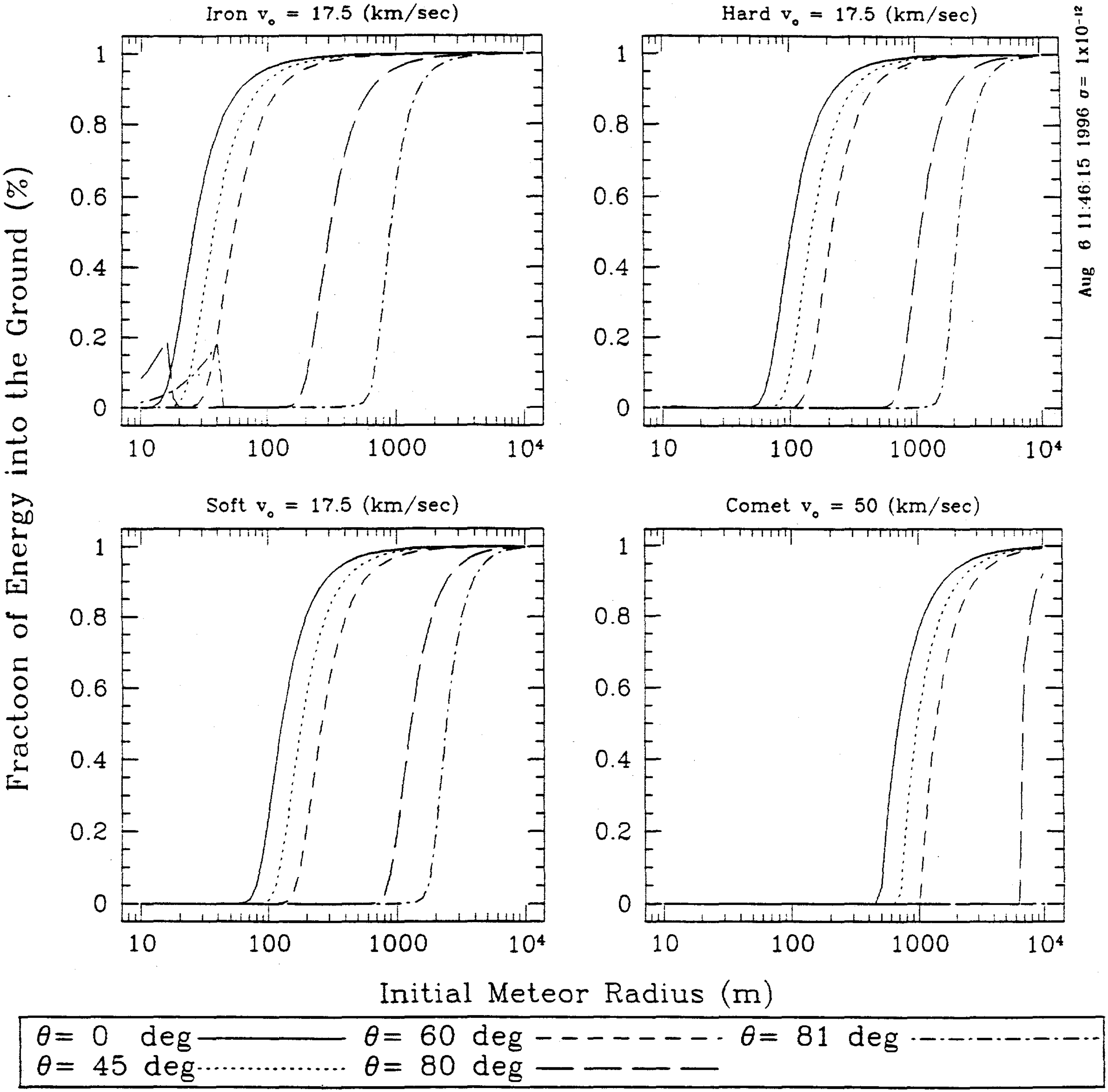

Fig. 8. The fraction of the initial kinetic energy that goes into the ground impact. This is given as a function of zenith angle for principal asteroid types. The results allow for ablation