This extract shows a selection of (non-paginated) pages from the book.

Preface

My intended audience is the science aware and interested; amateur astronomers; and those who wish to study astronomy at undergraduate level. My aim is that this book is suitable for the general reader.

There have been many books and articles written about the solar system asteroids. These range from the sensational (which do not always give an accurate scientific perspective) to in-depth research papers and conference proceedings of the International Astronomical Union. This booklet aims to:

- Give an overview of our current knowledge of asteroids within a scientific and factual context;
- Provide the reader with the necessary information to be able to read advanced works, treatises and research papers in the field;
- Put in perspective research findings, and events such as the Chelyabinsk impact;
- Provide a suitable basis for an undergraduate level short course on the asteroids;
- Encourage and inspire readers to follow their own lines of personal research.

This book is intended to be at an introductory, explanatory level. No preliminary knowledge of the subject matter, beyond school level science courses, is required. There is little mathematics in this booklet, but astronomy *is* a mathematical science so where needed, the maths used is fully explained.

The study of asteroids, and astronomy more widely, is a very dynamic and active science. Space probes are relaying data back to Earth literally daily, and theoretical papers are being issued every month. There are many areas of the science which are still not understood and this provides both challenges and opportunities for real advances to be made.

My aspiration is that this booklet can serve as the primer for the reader to delve deeper into this most fundamental of sciences and to inspire learning and researches. I wish you years of enjoyment.

Acknowledgements

In writing this book I am indebted to the scientists throughout history up to the present day who through their hard work, inspirational genius and frequent sacrifices have made such great inroads and insights into our science. This book uses the results and works from innumerable astronomers and mathematicians. The specific texts which I have used most often as works of reference are included in the Bibliography and References sections, and I gratefully acknowledge the authors of these works.

I also wish to acknowledge my more personal gratitude. First and foremost, I wish to both recognise and thank my teachers. I refer specifically my tutors at Teesside Polytechnic and in particular John R Dormand, Peter J Prince and Alan W Bush; and my lecturers at Queen Mary University London and in particular Iwan P Williams and John C B Papaloizou. Together with the inspirational physics teacher I had at Whitby school, Mr Wallace, they have given me a lifelong passion for astrophysics.

My passion however would have stayed just that, and unwritten had it not been for the support and encouragement of Elaina Taylor, Adam Poundall, Amanda Taylor and John Malaney; my proof-readers Janet Hyde, Adam McMurchie of the SSIG (Scottish Space Interest Group) and Kym Smith. To each of these I owe an un-redeemable debt to which I can merely offer my heart-held appreciation towards. However, I am without saying solely responsible for any omissions or errors which have found their way to the final print.

Glossary of Orbital Terms

Aphelion (Q)	The point in an asteroid’s orbit when it is furthest away from the Sun.
Astronomical unit (AU)	The semi-major axis of the Earth’s orbit (which is ~149.6 million km).
Direct orbit	An orbit where the object (e.g. asteroid) revolves around the primary attractor (e.g. the Sun) is the same direction of the rotation of the primary.
Eccentricity (e)	The degree to which an orbit is ellipsoidal. It can be thought of as how elongated the orbit is. A circle has eccentricity of zero, an open orbit (a *parabola*) has eccentricity of 1.0. Eccentricities of > 1 are *hyperbolic* curves and are used to describe events such as flybys.
Heliocentric orbit	The orbit of an object moving around the Sun.
Inclination (i)	The tilt of the asteroid’s orbit compared to the plane of the solar system.
Orbit	The closed path an object takes in its motion within a gravitational field.
Orbital period (P)	The time it takes for an object to complete one revolution around the centre of mass of the system (i.e. the Sun in the case of asteroids).
Perihelion (q)	The point in an asteroid’s orbit when it is closest the Sun
Opposition	The point in an object’s orbit when it is in directly the opposite direction (180°) to the Sun when viewed from Earth.
Precession (orbital)	The gradual rotation of the orientation of the planet/asteroid’s orbit. This is usually described as the precession of the perihelion point. Over time, the direction of the perihelion point (as seen from the Sun) will complete a full circle.
Retrograde orbit	An orbit where the object (e.g. asteroid) revolves around the primary attractor (e.g. the Sun) is the opposite way to the rotation of the primary.
Semi-major axis (a)	The average distance of the orbiting object asteroid from the Sun.

Common abbreviations

ASI	Agenzia Spaziale Italiana
ESA	European Space Agency
IAU	International Astronomical Union
JAXA	Japanese Aerospace exploration agency
JPL	Jet Propulsion Laboratory
KBO	Kuiper Belt Object
MPC	Minor Planet Centre
NEA	Near Earth Asteroid
NEO	Near Earth Object – an object coming within 0.05AU of the Earth
PHA	Potentially Hazardous Asteroid – an asteroid with realistic potential to impact the Earth
TNO	Trans-Neptunian Object – an object with semi-major axis greater than the planet Neptune’s

1. What is an Asteroid?

Asteroids are perhaps one of the most diverse ranges of objects within the solar system and without doubt the most numerous objects. They are classified according to their size, orbit and position within the solar system and for many years their nature was unknown. They are all (astronomical speaking) small – one of the largest (and first to be discovered) Ceres has a diameter of just 952 kilometres (Ceres however is now defined as a dwarf planet). Observed from Earth using anything but the largest of telescopes, they cannot be resolved into anything more than a star-like image. Indeed, the term 'asteroid', first proposed by William Herschel (b.1738 d.1822) in 1802, after a suggestion to him from the Greek expert Charles Burney (junior), is derived from the Greek *asteroeides*; 'star-like'.

Tremendous progress has been made in observation and research on asteroids over the last few decades. This in part is because of the devastating effect on humankind an asteroid impact on Earth would have. More scientifically, they also give us the opportunity to determine and test models of the solar system and planet formation, gravitational and non-gravitational dynamics, and planetary science to name but a few areas. They are often discussed in a wider context including comets and meteors, and for example the International Astronomical Union (IAU) has a conference series within standing committees (commissions 15 and 20) specifically for the integrated study of Asteroids, Comets and Meteors (ACM).

This booklet takes an asteroid specific view. But before we look at this class of object, we need to make some basic definitions of object distinguishing terms. Here we will use the terms:

Comet – to mean an object on a high eccentric (e generally > 0.75) heliocentric (orbiting the Sun) orbit; predominately icy in nature with cometary 'tails' visible at / near perihelion (the position in an orbit when an object is closest to the Sun);

Dwarf planet – to mean a largely spherical body (in hydrostatic equilibrium) within a heliocentric orbit, but which has a small gravitational Sphere of Influence and thus has not cleared its near orbital region of all other material. We also use here 'minor planet' as synonymous with 'dwarf planet';

Meteoroid – to mean a small rocky object of size less than 10 metres in dimensions, in heliocentric orbit but approaches close to Earth at some stage in its orbit and lifetime. A *Meteor* is when a Meteoroid enters the Earth's atmosphere; and a *Meteorite* is any part of the Meteor which survives the passage through the atmosphere and leads to a Meteoroid fragment reaching the surface of the Earth.

Asteroid – to mean one of the set of objects smaller than a dwarf planet but larger than a meteoroid, and orbiting the Sun within the orbital distance of Neptune. We will define other objects and specific types of asteroid as we discuss them throughout this booklet.

Observationally, asteroids (of whatever size) are quite distinct from comets. Asteroids do not form dust or gas trails (although as we will discuss later there are always exceptions!) and they do not form a fuzzy 'coma' as most comets do when they come closer in their orbits to the Sun. However, neither asteroids nor comets, because of their size and nature, have distinguishing or distinctive surface markings which can serve to identify them uniquely. Identification and recovery of previously observed objects could then be a significant issue.

Fortunately for us, this problem was solved in the late 1890s by the great French astronomer François Felix Tisserand (b.1845 d.1896) who showed that a number derived from an object's orbital parameters can be used as a unique identifier. This is described in detail in sections 4 and 10. The Tisserand criterion (often referred to as the Tisserand invariant) is a unique number assigned to each comet and asteroid, and is always one of the first analyses undertaken when an unknown or suspected new asteroid is observed.

1.1. Designation and Naming

In addition to the technical Tisserand criterion, asteroids are also assigned a sequential number and, usually, a name. The asteroid number and / or name are the usual ways in which to refer to the object. The process of naming asteroids is defined by the International Astronomical Union (and the MPC – Minor Planet Centre – operating at the Smithsonian Astrophysical Observatory).

When an object is first observed and cannot be identified as a previously seen and designated object, an initial identifier is given based on the year of discovery followed by two letters. The first letter indicates the month (24 letters are used alphabetically; excluding I and Z) to indicate which half of which month), and the 2nd letter (I is not used) is the order within the month in which the asteroid was discovered (for if more than one asteroid is discovered in that month). So for example, 2016 CG is the 7th (the 'G') asteroid to be discovered within the first half of February (the 'C') in the year 2016.

If more than 25 asteroids are discovered within any half-month a number is appended to the second letter to indicate how many cycles of the 25 alphabetic characters have been used. So for example, 2016 CG_1 was the 7th asteroid discovered in the latter half of February 2016, whereas 2016 CG_2 was the 32nd discovered within that time period. See 'Online sources' [1] for further details.

Once the object has been observed sufficiently enough for its orbit to be determined (this is generally after at least 2, normally 4, oppositions for the object) it is given a permanent numerical designation (e.g. 3663) by the MPC. This number is a sequence number which started at 1 (for Ceres) and to date is at a little over 468,000. Proper names are then invited to be submitted by the discoverer and are formally decided upon by the CSBN (Committee for Small Body Nomenclature) of the IAU.

Proper names of asteroids also follow certain conventions. Scientist's names are often used (3663 Tisserand is an example) and mythological names are also common. The Trojan asteroids (which we will see later are associated with Jupiter) are named after heroes and characters from the Trojan Wars; the Greeks one side of Jupiter, the Trojans on the other! See 'online sources' [2] for further details.

2. Discovery of the asteroids

As at May 2016, 714,490 asteroids have been identified. Of these, just under 95% are within what is known as the 'main belt', a region between the orbits of Mars and Jupiter, extending from a heliocentric distance of 2.0 to 3.2AU. There had been considerable speculation in the 18th century that a planet should lie within this region following the publication of the 'Titius-Bode' relationship.

2.1. Titius-Bode relationship

In 1766 the German astronomer Johann Tietz, later referred to as Titius, (b.1729 d.1796) published a book highlighting an apparent pattern within the semi-major axes (mean distances) of the then known planets. The pattern had been recognised earlier, probably at the start of the 17th century. This was popularised by another Austrian astronomer Johann Bode (b.1747 d.1826) and has become known as the Titius-Bode relationship. It is of historical importance but the relationship is not based upon any discernible physical laws or relationship.

In essence, the relationship states that by taking a simple arithmetic sequence the planetary distances, in units of AU (astronomical unit – the mean distance between the Sun and the Earth) can be determined. By using the numbers in the sequence 0, 3, 6, 12, 24… as x within the expression:

$$a = 0.4 + x/10$$

The following table can be constructed:

(x)	Titius-Bode value (a)	Planet	Actual semi-major axis (a) of planet
0	0.4	Mercury	0.38
3	0.7	Venus	0.72
6	1.0	Earth	1.00
12	1.6	Mars	1.52
24	2.8		
48	5.2	Jupiter	5.20
96	10.0	Saturn	9.54
192	19.6	Uranus	19.19
384	38.8	Neptune	30.07

Table 1 Titius Bode relationship

The planet Uranus was discovered (by William Herschel) visually and by chance, in 1781. Bode, who was working at the Berlin observatory (he later became its director) calculated the orbit of Uranus. He noticed that although the planet had been recognised by Herschel as a new-found planet, it had in fact been observed earlier and, for example, was included in John Flamsteed's (b.1646 d.1719) star catalogue *Historia Coelestis Britannica* of 1712 and 1725. This allowed Bode to determine the semi major axis of Uranus and once this was seen to be close to the Titius relationship, this gave credence to the relationship. A search was instigated for the missing planet at a distance of 2.8AU from the Sun. The first main belt asteroid to be discovered, Ceres, was found in 1801 and once its orbit was computed (it has semi-major axis of 2.77AU), it gave empirical credence to the 'law'.

However, the relationship breaks down for Neptune (discovered in 1846) and the 'law' is not now considered to be of significance. The satellites of the Jovian planets (i.e. Jupiter, Saturn, Uranus and Neptune) do not follow such a rule, and in any stable orbital configuration (such as the major planets are in) there will always be a series relationship of this form that can be deduced

2.2. Main belt asteroids

Ceres was discovered in January 1801 by the Italian astronomers Giuseppe Piazzi (b.1746 d.1826) and Niccolo Cacciatore (b.1770 d.1841) and takes its name from the Roman goddess of agriculture. Whilst working in January 1801 at the Palermo Observatory, Sicily, updating and correcting the Taurus region of a star catalogue they recorded an object which had not previously been seen. Further observations over the following nights showed the object was moving against the background of stars. By March 1801 its nature as a new astronomical body within the solar system had been established.

On March 28th in the following year, Heinrich Wilhelm Olbers, (b.1758 d.1840) whilst observing from Bremen and cataloguing stars within the Virgo constellation, partly to aid recovery and monitoring of Ceres, detected a star-like image which he was sure had not been there in the January. He observed the object for several hours and could detect its proper motion within that timescale. Olbers had discovered the second asteroid, the main belt object now known as 2 Pallas.

In June of 1802, Olbers proposed that both Ceres and Pallas were fragments of the missing-planet and so the search for further objects in this region of the solar system continued. The German astronomer Karl Ludwig Harding (b.1765 d.1834), observing from Lilienthal, near Bremen and diligently searching the regions of Cetus and Virgo (on the basis that it was considered fragments of a disintegrated planet may be in the same region) found the third asteroid on the 1st September 1804. This was the main belt asteroid 3 Juno, named after the Roman goddess and queen of the gods.

Astronomers continued their search of and for these new objects and after many months of careful observations, on 29th March 1807 Olbers discovered the 4th asteroid (his 2nd) in the same region as the earlier discoveries had been made. The new asteroid was named Vesta by the German mathematician Carl Friedrich Gauss (b.1777 d.1855) after the Roman goddess of the family and home.

However, the rate of new asteroid discoveries then slowed dramatically until 1845 with the fifth asteroid, Astraea (named after the Greek goddess of innocence and purity). It was discovered by the German amateur astronomer, and postmaster by day, Karl Ludwig Hencke (b.1973 d.1866) following 15 years of dedication, commitment and systematic observations. This reduction in discoveries was probably skewed by the lack of very accurate star catalogues, a general feeling (such as advised by the then director of the Paris Observatory, Jean Baptiste Delambre) that systematic stellar catalogues offered better scientific advantages, and an implied pre-disposition to look in the regions of space near to the already discovered asteroids and their orbital intersections.

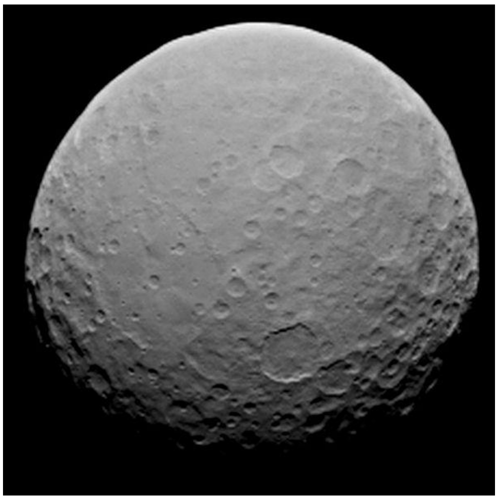

Figure 1 Minor planet Ceres
Imaged by NASA/Dawn mission on 19th February 2015 from 46,000km

Following Hencke's discovery, new impetus was given to the search for asteroids and many more discoveries followed. Asteroid 6 Hebe was also found by Hencke in July of 1847; the first British asteroidal discoveries were 7 Iris (August 1847) and 8 Flora (October 1847) both discovered by John Russell Hind (b.1823 d.1895) from an observatory in Regents Park, London. By the end of 1850, 13 asteroids had been detected, and by1857 a total of 50 asteroids (all main belt) had been discovered.

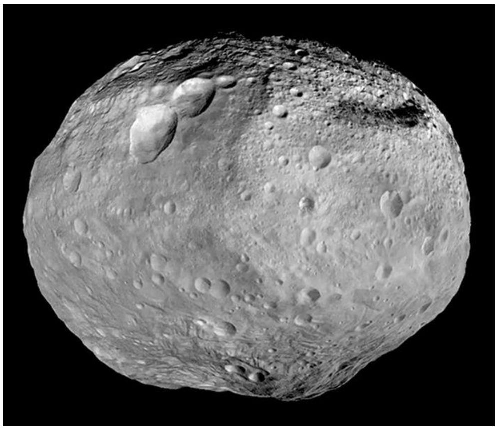

Figure 2 Minor planet Vesta
Composite Image by NASA/Dawn mission on 11th Sept 2012

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3. Orbits of the asteroids

There are few regions within the solar system where asteroids are not or have not, at some time, been observed. In this chapter we will look at the orbits and locations of the different types of asteroids.

3.1. Main belt

The main belt of asteroids within the solar system contained ~677,000 (676,830 as at May 2016) objects; almost 95% of all known asteroids. The main belt is segmented into three distinct regions, based on heliocentric distance. The orbital characteristics, and volumes, for these regions are:

Segment of belt	Number of objects	Range of Semi major Axes (a) (AU)	Range of orbital eccentricity (e)	Range of orbital inclination (i) (º)
Inner	13,325	1.7 < a < 2.0	0.000 < e < 0.165	0.5 < i < 55.4
Central	641,934	2.0 < a < 3.2	0.000 < e < 0.474	0.0 < i < 67.6 *
Outer	21,571	3.2 < a < 4.6	0.000 < e < 0.693	0.0 < i < 84.4

Table 3 Segments within main belt

* One Main Belt asteroid (2010 EQ169) has an orbital inclination of 91.6%, i.e. a retrograde orbit.

We noted (section 2.2) the main belt is not a ‘continuum’ of orbits and the Kirkwood gaps are regions where no asteroid can remain in a stable orbit. The gaps are caused by the regularity of gravitational effects, exerted by Jupiter, that any object orbiting at these distances would experience. For example, the gap at semi-major axis of 2.5AU is the 3:1 resonance of Jupiter’s period. This means any object at that distance would cover three orbits in the same time as it takes Jupiter to complete one orbit.

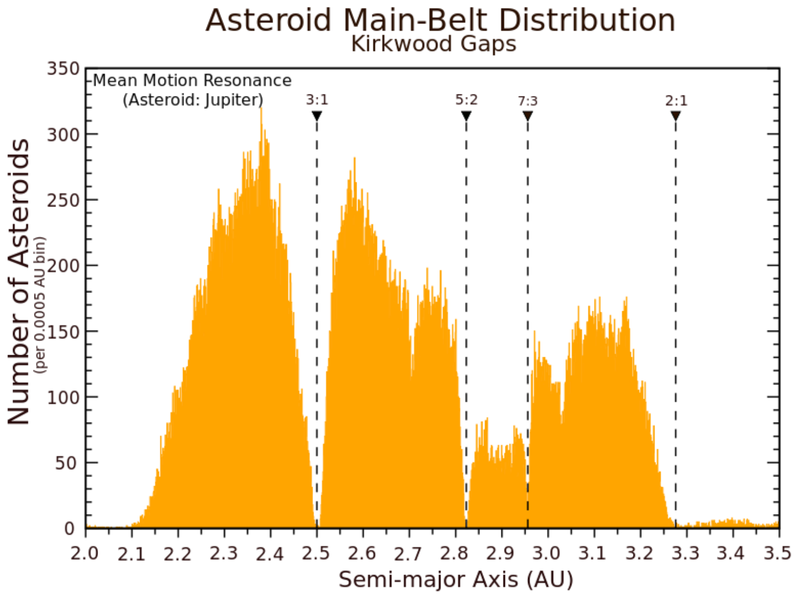

Figure 4 Main belt Kirkwood gaps

Gravitational theory (and Kepler’s 3rd law in particular) shows that orbital period (P) of a planet or object can be related directly to that object’s semi-major axis (a). The relationship is:

$$P^2 = \frac{4\pi^2}{G(m_1 + m_2)} a^3$$

where m_1 and m_2 are the masses of the Sun and the planet respectively.

If we use units of Earth years for P and AU for a, then the equation simplifies to

$$P^2 = a^3$$

For our case of the 3:1 resonance. We know that the orbital period of Jupiter is 11.86 years and its semi-major axis is 5.2AU. An asteroid at the 3:1 resonance would have an orbital period of 1/3rd that of Jupiter (i.e. 3.95 years). Using this value for P in the formula above gives a semi-major axis value ‘a’ of 2.50AU. There are no asteroids within the main belt (or elsewhere) which have this semi-major axis. Any asteroid which had an orbit, or an orbit which by perturbations resulted in an orbit at this distance (and orbital period) would be unstable and be rapidly (astronomically speaking, < 100 years) removed. 2010 HX48 has ‘a’ of 2.4999AU and is very close to the resonance, although will not be there for long! We will look at orbital changes and migrations in more detail later (section 4)

Figure 5 Main belt asteroid 253 Mathilde
Imaged by NEAR/Shoemaker probe on 27th June 1997 from distance of 2400km

None of the main belt asteroids are NEO or PHAs. The distribution of semi-major axes of objects with the main belt, especially the central area, is punctuated by the Kirkwood gaps named after Daniel Kirkwood (see section 2.2). These gaps correspond to areas of specific and regular gravitational resonances with respect to the orbital period of Jupiter.

3.1.1 Mars crossing asteroids

This type of asteroid, currently numbering 14568, transcends the main belt limits and has perihelion distances from 1.300AU up to 1.666AU – the aphelion distance of the Martian orbit (and approximately the distance at which the inner main belt is defined to ‘start’). This class of asteroids have aphelion distances within the orbital radius of Jupiter (5.2AU) and currently, range from 1.37AU to 5.053AU. As such, their orbits are completely within the space between the Earth and Jupiter. The first of this class discovered was 132 Aethra when 13th June in 1873 it was found by the Canadian James Craig Watson (b.1838 d.1880) whilst he was director of the Detroit Observatory.

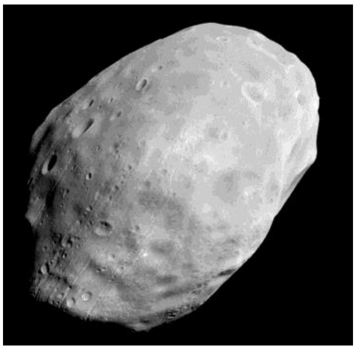

Figure 6 Phobos, Mars’ largest moon
Imaged from distance of 9700km by NASA’s Mars Global Surveyor on 1st June 2003

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4. Orbital evolution

As we have seen, with the exception of the Vulcanoids, asteroids are found in all regions of the solar system. However, we have also noted that many of the asteroids, particularly those outside the main belt, are on chaotic/unstable orbits and come under the influences of gravitational perturbations from the major planets. However, whilst gravitation is the dominant perturbing and orbit-changing effect, it is not the only disturbing effect. We look here at gravitation, together with other significant effects.

4.1. Gravitational dynamics

Many asteroids are on orbits which take them close to the major planets. On near approaches, the orbit of the asteroid is changed. This can be modelled to a high degree of accuracy using Newtonian gravitation and in particular with a mathematical model known as the ‘restricted 3-body problem’. This is where the asteroid is considered of negligible mass compared to the Sun and the major planet, or in other words, the gravitational influence of the asteroid’s mass on the major planet and the Sun can be ignored. In the case of asteroids, the model is very appropriate and accurate; the mass of the most massive of all asteroids, Ceres, is less than one-millionth (10^{-6}) that of Jupiter and just one ten-thousandth (10^{-4}) that of the Earth.

We noted in section 1 that Francois Tisserand determined the orbital invariant which remained constant before, throughout and after such a gravitational encounter. The Tisserand criterion T_c relates semi-major axis, orbital eccentricity and orbital inclination and is:

$$T_c = \frac{1}{2a} + \sqrt{a(1-e^2)}\cos i$$

The criterion defines a constant number which does not alter however many times an asteroid may encounter a massive object and ‘suffer’ orbital perturbations. The criterion is applied by recognising both pre and post-encounter T_c values (numbers) are the same. In equation form this means that:

$$T_c = \frac{1}{2a_b} + \sqrt{a_b(1-{e_b}^2)}\cos i_b = \frac{1}{2a_p} + \sqrt{a_p(1-{e_p}^2)}\cos i_p$$

where the suffixes b and p refer to the value of the orbital parameter before-encounter and post-encounter. Tisserand’s criteria gives a single (most likely unique) number by which to refer to an asteroid (or comet), and when a new or recovered asteroid is observed, the first thing which astronomers do is to calculate its orbit and its Tisserand number.

It should be noted however that the Tisserand criteria used by the Minor Planet Centre and NASA’s Jet Propulsion Laboratories (JPL) is a modified form of T_c and their measure (T_j) is parametrised against the semi-major axis of Jupiter (a_j). The calculated values by those organisations result from the equation:

$$T_j = \frac{a_j}{a} + 2(a/a_j)^{0.5}\sqrt{(1-e^2)}\cos i$$

Tisserand derived this invariant from the Jacobi integral, named after the German mathematician Carl Gustav Jacobi (b.1804 d.1851). We provide an alternative (less rigorous) derivation in section 10.1 based on conservation of angular momentum and orbital energy.

The gravitational interactions between masses is more generally known by the name perturbation theory. Gravitational systems involving more than two massive objects are very complex to solve, and only very specific cases of analytical (formula-based) solutions are available even in the case of

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(Extract from section 4.3…)

We can use energy considerations (and Kepler's laws) to determine orbital velocity. The orbital velocity of an asteroid in heliocentric orbit with semi-major axis a and at a distance r from the Sun is given by the formula:

$$v^2 = GM\left(\frac{2}{r} - \frac{1}{a}\right)$$

where G is the universal constant of gravitation and M is the mass of the Sun. (A derivation of this formula can be found in bibliography [3]). Taking the example of a main belt asteroid of semi-major axis 2.8AU in a circular orbit ($e = 0$), and hence $r = a = 2.8$ we find its orbital velocity as 17.8km/s.

Now, if we also look at the orbital velocity of say an Amor class asteroid on an elliptical orbit of a = 3.2AU, its speed at 2.8AU will be 18.8 km/second. Looking at the respective orbital directions we can approximate the collision here as a tangential strike and the resultant velocity of impact will be ~25.9 km/second. (See figure 14 – side impact)

We will then compare this to the escape velocity of the larger object. Escape velocity is the speed (radial velocity from the centre of mass of the object) that a particle/object must reach to break free of (attain a hyperbolic orbit with respect to) the larger mass. For a spherical object the escape velocity v_e can be determined from:

$$v_e = \left(\frac{2Gm_a}{R + h_a}\right)^{0.5}$$

where m_a is the mass of the larger object, R its radius, and h_a the distance of the 'escapee' above the surface of the larger mass. (Again, a derivation of this formula can be found in bibliography [3] to which the mathematically interested reader is referred). Looking at an extreme, we can calculate the surface level escape velocity for Ceres, the largest asteroid. This works out to be 0.515 km/second (The Earth's surface level escape velocity for comparison is 11.2 km/second).

However, for more median sized asteroids, say a typical main belt asteroid with dimension of ~10km and density of 3.0 g/cm^3 (the typical density of stony, chondrite meteorites) the escape velocity is around than 1 m/second (1.4 m/seconds for a homogeneous sphere of this size and density).

Collision dynamics within the main belt will have impact velocities between ~0.01 km/second where co-orbiting objects merge by very slow 'catch-up', through transverse (sideways) impacts, up to ~4 km/second for 'head-on' collisions of asteroids on retrograde and direct orbits respectively.

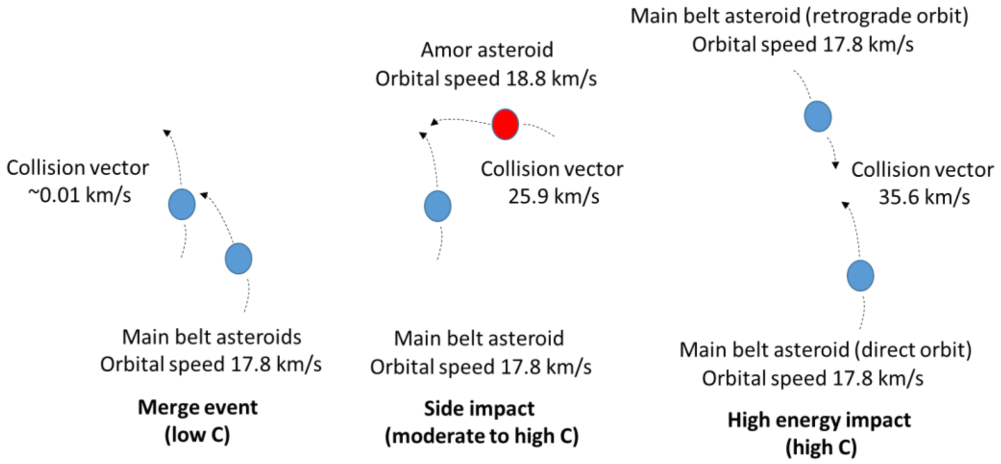

Figure 15 Collision scenarios

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(Extract from section 8.3…)

Very few binary Trojans have been detected (although this may be due to observational bias – i.e. they're difficult to find). The Jovian Trojan 617 Patroclus was the first to be identified as binary, its secondary being discovered in September 2001, and is one of only four Jovian Trojans definitively known to have binary companions detected.

Figure 16 Main belt asteroid 243 Ida and moon Dactyl
Image of 243 IDA taken on 28th August 1993 from range of ~10,500 km by NASA Galileo mission
Ida at 31km dimensions dwarfs its tiny moon, Dactyl, seen to the right in this image.

Observational bias may also explain in part why there are very few binary centaurs known. The two thus far discovered are 42355 Typhon (2002 CR46) whose companion Echidna was detected in January 2006; and 65489 Ceto (2003 FX128) whose companion Phorcys was discovered in April, 2006. Of the Trans-Neptunian objects, the discovery of Charon, the largest moon of Pluto, in June 1978 was 'technically' the first TNO binary to be discovered. However, Pluto's previous designation as a planet may perhaps mean that 1998 WW31 should retain the 'honour' of being the first binary TNO to be detected when its companion was found in December 2000.

In total, there are currently ~285 confirmed binary pairs identified. This number includes 12 triple or multiple systems. There are a similar number of unconfirmed, suspected, binaries. Current estimates of the frequency of binary asteroid vary, with most assessments being of the order of ~2% of all main belt asteroids. Estimates for NEOs and planetary orbit crossing asteroids are higher at circa ~10%, probably due to the gravitational disruptions, hence fragmentation, this class of asteroids experience.

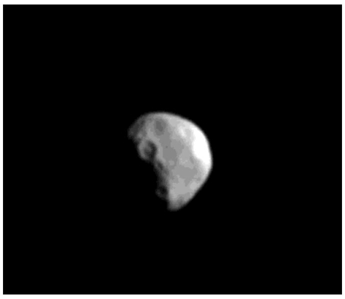

Figure 17 Dactyl satellite moon of 243 Ida
This image shows the best view of the 1.4km diameter moon. Taken from 4000km by Galileo probe.

Of the known binaries, some pairs have very similar masses / sizes, e.g. the components of 617 Patroclus (Jovian Trojan) have dimensions of 106km and 98km diameters; whilst others have markedly different masses / sizes, for example the main-belt asteroid 22 Kalliope (166km) has named secondary Linus (28km). Perhaps the most 'famous' binary asteroid, 243 Ida (31km) has the companion Dactyl (1.4km) and is more representative of most binary asteroids.

<……Subsequent pages omitted from extract….>

(Extract from section 9.1…)
The associated thermal and shock waves would have eradicated all life forms within several hundred kilometres. Releasing an energy of up to 35 gigapascals, the event would have measured well in excess of 9 on the Richter scale. Yet as asteroid impacts fare, this was a small event! The Chicxulub event was due to an asteroid impact of dimension ~10km. The interested reader is referred to reference [10] for further details on the Limousin impact.

Figure 18 Rochechouart lithic breccia
(The church of St. Sauveur in Rochechouart town centre is partly constructed using breccia stone.)

9.2 Potentially hazardous asteroids collision risks

Whilst all Earth crossing asteroids could potentially be PHAs, orbital inclination, position / direction of ascending and descending nodes, and gravitational resonances are all key factors. Of the circa 15,000 NEOs known, approximately 12% (1730) are PHAs, and of these around 600 have non-discountable risk of collisions within Earth within the next hundred years. It is not a case of ‘if’, but ‘when’ a significant asteroid collision will occur; unless we mitigate the potential for collision.

Whilst orbital ephemerides can be determined based on a relatively low number of observations, it is not an exact science for PHAs. NEOs are especially susceptible to orbital gravitational perturbations. These can be well modelled and are important as NEO orbits cross the orbits of, and come close to, the inner planets. They also pass relatively close to the Sun (and thus tidal effects are also a factor).

Additionally, non-gravitational forces (see section 4.2), and especially the Yarkovsky effect (see section 4.2.3) are important factors in orbital changes for NEOs. The latter effect cannot be modelled accurately because the effect is dependent upon the nature of each specific asteroid. Consequently, NEO, and PHA, orbits cannot be accurately determined and there is always a degree of uncertainty (error) in orbital elements, and thus uncertainty in predicted position and time.

9.2.1 Asteroids on collisional paths.

On our current state of knowledge, the four most likely sizeable asteroids that *will* impact Earth in the relative near future are:

99942 Apophis (2004 MN4)
Discovered in June 2004 from the Kitt Peak observatory, Arizona, this Aten class asteroid (a: 0.92 AU, e: 0.19, i: 3.3°, P: 0.89yrs) is appropriately named after the Egyptian god of evil and destruction. It made a relatively close approach to the Earth on the night of 21st December 2004 when it came within 145,000 km. This is about 1/3rd of the Earth-Moon separation. Based on the multiple observations taken at that time, it was predicted there was a significant probability that at its 2029 encounter with the Earth, a collision would occur. It became widely publicised in the public domain and, unsurprisingly, significant interest and concern was taken by the scientific community and government authorities. Radar and optical observations collated prior to, during and since the 2004

encounter have all been collated and the orbit, together with potential gravitational and non-gravitational perturbations, has been modelled and simulated.

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