Meteoroid bulk density and Ceplecha types

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Abstract

Determination of asteroid bulk density is an important aspect of NEO characterization, yet difficult to measure. As a fraction of meteoroids originate from asteroids (including some NEOs), a study of meteoroid bulk densities can potentially provide useful insights into the densities of NEOs and PHOs in lieu of mutual perturbations, satellite, or expensive spacecraft missions.

NASA's Meteoroid Environment Office characterizes the meteoroid environment for the purpose of spacecraft risk and operations. To accurately determine the risk, a distribution of meteoroid bulk densities are needed. This is not trivial to determine. If the particle survives to the ground the bulk density can be directly measured, however only the most dense particles land on the Earth. The next best approach is to model the meteor's ablation, which is not straightforward. Clear deceleration is necessary to do this and there are discrepancies in results between models.

One approach to a distribution of bulk density is to use a measured proxy for the densities, then calibrate the proxy with known densities from meteorite falls, ablation modelling, and other sources. An obvious proxy choice is the Ceplecha type, K_B, thought to indicate the strength of a meteoroid.

K_B is frequented cited as a good proxy for meteoroid densities, but we find it is poorly correlated with density. However, a distinct split by dynamical type was seen with Jovian Tisserand parameter, T_J, with meteoroids from Halley Type comets ($T_J < 2$) exhibiting much lower densities than those originating from Jupiter Family comets and asteroids ($T_J > 2$).

Ceplecha types

In 1958, Ceplecha introduced a parameter, K_B, that he saw as a measure of the strength of a meteor and was linked to meteoroid densities (Ceplecha, 1958).

It was noted that the beginning heights, H_B, of meteoroids were correlated to their strength based on measured H_B of more porous meteoroids (Draconids) or more dense meteoroids (Geminids). H_B is most affected by velocity, but separate bands can clearly be seen when plotting H_B against velocity. Ceplecha thought these bands were correlated with meteoroid strength.

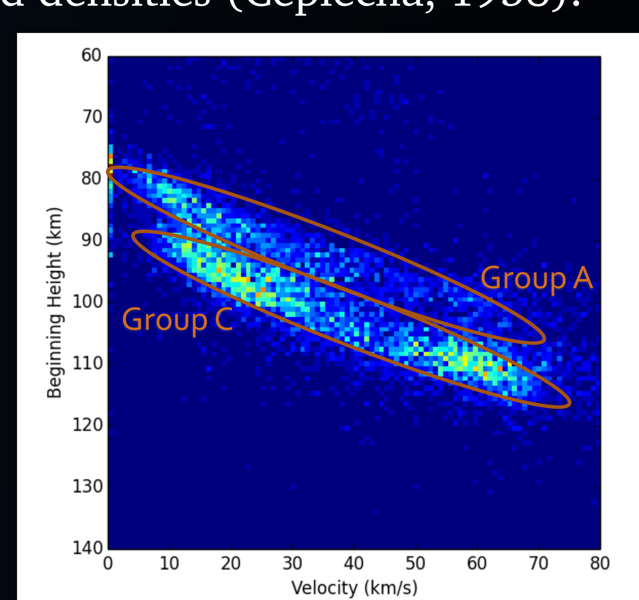

Figure 2: Heat map of beginning height vs. velocity for sporadic meteors seen in NASA's Wide-field camera network.

What is K_B? Based on a expression from Levin (1956) for surface temperature of a meteoroid per height:

$$\tau(0,h) = \frac{\alpha}{2\sqrt{\lambda\delta cb}}\rho v_{\infty}^{\frac{5}{2}} cos^{-\frac{1}{2}}(z_R)$$

$\tau(0,h)$ is surface temperature at a height
λ is heat conductivity
δ is meteoroid density
α is the accommodation coefficient
c is the specific heat of the meteoroid material
b is the air density gradient
z_R is the zenith distance of the radiant
v_∞ is the approach velocity
ρ is the air density

If the surface temperature and air density are set to values at the meteor beginning height. Ceplecha put all the physical constants on one side and observable quantities on the other, and set the physical constants are set to K_B:

$$K_B = \log(\rho_B) + 2.5\log(v_\infty) - 0.5\log(\cos(z_R))$$

Where K_B is a function of material constants and surface temperature, and changes in K_B are strongly tied into the composition of the meteor.

Ceplecha (1958) found several K_B groups that show up when isolating the meteors and K_B values by velocity and orbital type, as seen in Table 1 and Figure 3.

Table 1: Groups of meteors according to Ceplecha (1988).

Ceplecha Group	K_B Range	Orbital Criteria
Asteroidal	$8.00 \leq K_B$	
Group A	$7.30 \leq K_B \leq 8.00$	
Group B	$7.10 \leq K_B \leq 7.30$	$q \leq 0.30$ AU
Group C1	$6.60 \leq K_B \leq 7.10$	$a < 5$ AU, $i \leq 35^\circ$
Group C2	$6.60 \leq K_B \leq 7.10$	$a \geq 5$ AU
Group C3	$6.60 \leq K_B \leq 7.10$	$a < 5$ AU, $i > 35^\circ$
Group D	$K_B < 6.60$	

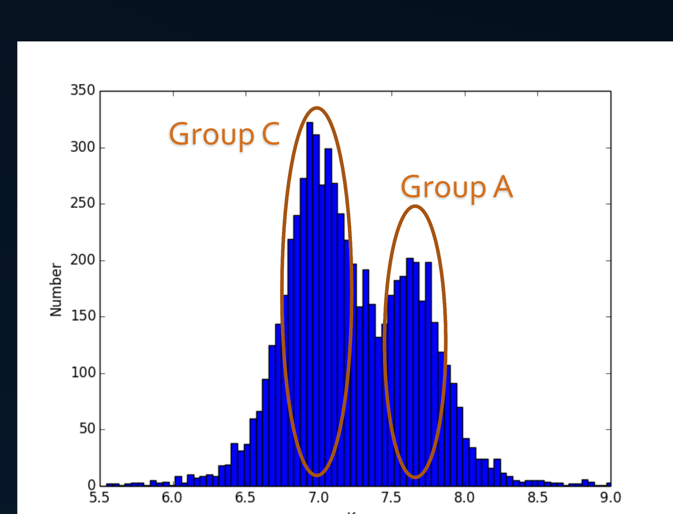

Figure 3: Distribution of K_B as seen in NASA's Wide-field meteor cameras.

These groups show up clearly on a H_B vs. velocity graph, further confirming Ceplecha's suspicion they are tied to the meteoroid strength.

Meteoroid densities associated with Ceplecha types

In order to use K_B as a proxy for density distribution, the link between K_B and density must be established. The earliest studies on meteoroid bulk density were from the 1950's. Since then, many studies have been performed.

In examining the various sources that have linked density to K_B, the relationship was not as clear as one would hope and primarily based on studies that have significant biases or models that have since been disproven, such as single-body ablation. Other discrepancies likely stem from a paucity of data. Several of Ceplecha's papers relied on meteorite density data from two or three meteorite falls, or just one fireball (Ceplecha, 1977, 1988; Ceplecha et al., 1998). Table 2 shows seven of the best studies. Even within these studies, much is unclear and unknown. Note the discrepancies, particularly in Groups A through D.

Table 2: Average meteoroid density corresponding to different K_B groups.

Study	Density Method	Density by Ceplecha Group (g cm^{-3})					
		Irons	Ast	A	B	C	D
Ceplecha (1966, 1967)	Rough estimates using past work			4	2.2	1.4	
Revelle (1983)	Single-body ablation		3.7	1.85		0.93	0.34
Ceplecha (1993)	Three meteorite falls, other theoretical assumptions.		2.7-5.9	1.4-2.7	0.65-1.7	0.55-0.91	0.18-0.38
Ceplecha et al. (1998)	3 meteorite falls, known meteor shower parent bodies	7.8	3.7	2	1	0.75	0.27
Revelle (2001)	Uniform bulk density model + inhomogeneous porous model		3.7	1.85-2		0.75-0.93	0.27-0.34
Bellot Rubio et al. (2002)	Single-body ablation			2.4	1.4	0.3	
Kikwaya et al. (2011)	Ablation modelling with thermal disruption of 107 meteors			3.8		0.8	

The most thorough study of bulk densities through ablation modelling is Kikwaya et al (2011). They looked at 107 meteors observed by intensified cameras in Ontario, Canada and modelled the deceleration and light curves with an ablation model that includes fragmentation (Campbell-Brown & Koschny, 2004). They robustly searched the entire parameter space to determine fits to the data. A subset of the 92 events not associated with a shower was used. Campbell-Brown et al. (2013) inspected 10 meteors using the same model. Orbits and trajectories were given for the meteors. With this study, we look at trends in K_B.

The correlation between K_B and bulk density was not as strong as hoped. However, a clear relationship between Tisserand Parameter and density was seen. A Spearman Rank coefficient of 0.795 was found between density and T_J, and 0.441 between K_B and density, indicating a tighter correlation between T_J and density.

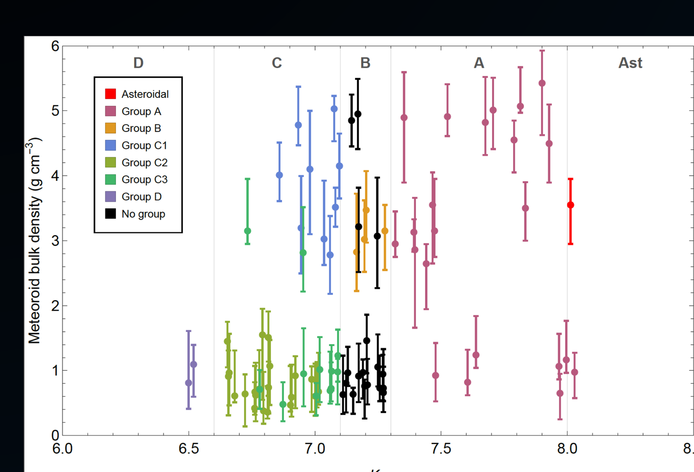

Figure 4: K_B against bulk density as found with ablation modelling for 92 meteors. (Kikwaya et al 2011.)

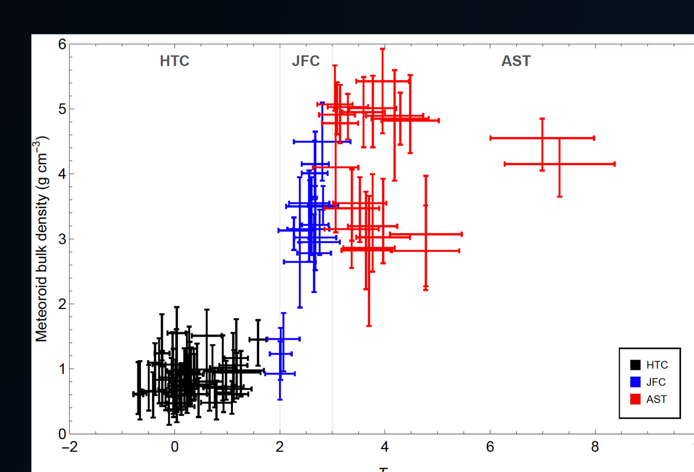

Figure 5: T_J against bulk density as found with ablation modelling for 92 meteors. (Kikwaya et al 2011.)

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

$\boldsymbol{a_J}$ = Jupiter's semi-major axis
$\boldsymbol{a, e, i}$ = semi-major axis, eccentricity, inclination of object

As Jupiter exerts the most dominant influence on comets and asteroids, the Jovian Tisserand parameter represents an object's orbit with respect to the Sun and Jupiter. Halley Type Comets have T_J below 2, Jupiter Family comets have T_J between 2 and 3, and most asteroids have $T_J > 3$. However this is not a hard cutoff as some comets have $T_J > 3$ and some asteroids have $T_J < 3$.

When comparing these results to comets and asteroids, one should note that these bulk densities are for small particles, $\sim 10^{-5}$ to 10^{-6} kg. The macroporosity of larger objects will change the overall bulk density. Carry (2012) shows reasonable porosities between 0 and 60%.

$$\mathcal{P}(\%) = 100(1 - \frac{\rho}{\rho_m})$$

$\mathcal{P}(\%)$ = macroporosity
$\boldsymbol{\rho}$ = asteroid bulk density
$\boldsymbol{\rho_m}$=bulk density of associated meteoroid

Conclusions

The task of determining meteoroid density distributions is complex and led to the investigation described in this report. In reproducing work done by Ceplecha (1977, 1988) to correlate K_B with bulk density, we examined the modeling of high-resolution meteor data from Campbell-Brown et al. (2013) and Kikwaya et al. (2011). The correlation between K_B and density was not as strong as hoped.

The Tisserand parameter of a meteoroid is a better indicator of the density than the strength proxy, a somewhat surprising result.

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