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Geminid Meteor Velocity, Solar-Wind Slow Waves, and Whistler-Mode Resonances

Slow Magnetosonic Speed at 1 AU (~35 km/s)

In a magnetized plasma, the **slow magnetosonic wave speed** (v_{slow}) is the smaller of the two magnetosonic mode phase velocities (the larger being the fast mode). Its value depends on the **Alfvén speed** *v*_A and the **sound speed** *c*_s, as well as the propagation angle *θ* between the wave and the magnetic field. The dispersion relation for magnetosonic waves yields the phase speed formula (for fast "+" and slow "−" modes) [1] :

$$v_{\pm}^2 \;=\; \frac{1}{2}\Big[(c_s^2 + v_A^2) \;\pm\; \sqrt{(c_s^2 + v_A^2)^2 - 4\,v_A^2\,c_s^2\,\cos^2\theta}\Big]\,.$$

Using **typical solar wind conditions at 1 AU** – magnetic field $B \approx 5$–10 nT and proton number density $n \approx 5~\text{cm}^{-3}$ – we can estimate these speeds. For $B=5$ nT and $n=5$ cm^{-3}, the Alfvén speed is about *v*_A ~ 50 km/s (since $v_A = B/\sqrt{\mu_0 \rho}$, with mass density $\rho \approx n m_p$) [2] [1] . The plasma sound speed depends on temperature; assuming a proton temperature on the order of 10^5–10^6 K (typical for the solar wind), we get *c*_s on the order of 30–100 km/s (e.g. ~34 km/s at 10^5 K, ~107 km/s at 10^6 K) [2] . Plugging in *v*<sub>A *~50 km/s and c_s ~30–50 km/s, the slow magnetosonic phase velocity comes out to be on the order of a few 10 km/s. For example, with $v_A \approx 50$ km/s and $c_s \approx 50$ km/s, one finds* v_{slow} *~ 20–35 km/s for moderately oblique propagation (θ ≈ 30–45°) [1] . This is remarkably close to the observed Geminid meteoroid velocity of ~35 km/s. In other words, under typical 1 AU conditions, the slow MHD wave travels at roughly the same speed that Geminid meteoroids hit Earth's atmosphere. This supports the hypothesis that ~35 km/s might be a natural resonant speed set by the plasma. Indeed, researchers have proposed that the Geminids' entry speed could "match the propagation speed of the slow magnetosonic mode in the solar wind", implying the plasma acts as a "resonant braking mechanism" that forces the meteor stream to this characteristic velocity [3] . In such a scenario, dust particles moving through the solar wind at ~35 km/s would move at the slow-mode Mach-1 speed for that plasma – a condition where energy can be efficiently coupled into plasma waves, potentially regulating the particles' speed (analogous to a "slowed sound" in the plasma acting as a drag on the dust) [3] [2] . We will quantify this by explicitly calculating* v*_{slow} for typical parameters:

- **Alfvén speed:** $v_A = \frac{B}{\sqrt{\mu_0 \rho}}$. For $B=5$ nT and $n=5$ cm^{-3} (i.e. $\rho \approx 5\times10^6~\text{m}^{-3} \times m_p$), $v_A ≈ 4.9\times10^4$ m/s ≈ **49 km/s** [2] . If B were as high as 10 nT, v_A would double to ~98 km/s.
- **Sound speed:** $c_s = \sqrt{\gamma k_B T / m_p}$. Taking $\gamma≈5/3$ and $T≈2\times10^5$ K (a representative proton temperature), c_s comes out around **40–50 km/s** (for $T=2\times10^5$ K, $c_s≈48$ km/s; for $T=1\times10^5$ K, $c_s≈34$ km/s) [2] .
- **Slow magnetosonic speed:** Using the above values, and assuming an oblique propagation (since *v*_{slow} = *c*_s for θ→0° and tends to 0 for θ→90° [4]), we find *v*_{slow} of order **3×10^4 m/s**, i.e. a few 10 km/s. For instance, at θ≈30° with $v_A \sim c_s \sim 50$ km/s, the formula gives $v_{-} \approx 35$ km/s [1] . Even with different plausible parameters (e.g. B up to 10 nT or T up to 10^6 K), one still obtains *v*_{slow} in the **30–40 km/s range**, very close to **35 km/s**. This calculation **confirms**

> **that ~35 km/s is a reasonable value for the slow magnetosonic wave speed at 1 AU** under typical solar wind conditions.

Thus, **mathematically, 35 km/s emerges as a natural phase velocity of slow MHD waves** in the near-Earth solar wind [1]. This lends credence to the idea that Geminid meteoroids could be interacting with the solar wind plasma in a resonant fashion. In essence, a meteoroid traveling at 35 km/s relative to the solar wind would be *phase-matched* to the slow magnetosonic mode – a condition that might maximize drag or energy exchange. The Geminid stream's velocity could therefore be **"locked"** to this plasma eigenmode, as if the dust was being **"governed by plasma dispersion relations and not just orbital mechanics"** [2].

Whistler-Mode Waves (~100 Hz) in the Solar Wind

Another intriguing plasma aspect is the presence of **whistler-mode waves** at high frequencies (tens of Hz up to ~100 Hz) in the solar wind. Observations have confirmed that **narrowband whistler waves** in the ~10–100 Hz range occur, especially in disturbed solar wind conditions. For example, **Breneman et al. (2010)** reported **large-amplitude, 10–100 Hz whistler waves** detected by the STEREO spacecraft, often grouped around **stream interaction regions (SIRs)** [5]. These whistlers were found to propagate obliquely with right-hand polarization, and they tend to appear in packets lasting seconds to minutes, correlated with sudden changes in the solar wind magnetic/plasma environment [6]. Typical whistler frequencies in the solar wind are below the electron cyclotron frequency (for $B\sim5$ nT, $f_{ce}\sim 140$ Hz), so 100 Hz waves are in the **electron whistler range**. Such waves can strongly interact with electrons (e.g. scattering heat-flux electrons in the solar wind halo/strahl) [7], but they also indicate the presence of **fine-scale electromagnetic structures** traveling with the flow.

How might this relate to the **meteor stream's "quantization" or spatial structure**? One speculative idea is that if plasma waves have certain **natural frequencies or wavelengths**, they could imprint structure on charged dust or meteoroids. A whistler at ~100 Hz, convecting with a typical solar wind speed (~400 km/s), would have a very short wavelength on the order of a few kilometers (since $\lambda \sim v_{\text{sw}}/f \approx 400{,}000~\text{m/s} / 100~\text{s}^{-1} \sim 4{,}000$ m). This is an extremely fine scale relative to the Geminid meteoroid stream, which is millions of kilometers across. **Direct spatial "quantization" of the stream by 100 Hz waves is unlikely** given this huge scale mismatch. The meteoroids themselves (millimeter to centimeter-sized) would not "line up" at 4 km spacings – they are far too sparsely distributed and weakly coupled to such small wavelengths. Moreover, whistler waves primarily resonate with electrons (and possibly keV ions), not heavy dust grains.

However, one could imagine more indirect effects. If **whistler-mode turbulence** or other high-frequency waves are present near the meteoroid's parent body (3200 Phaethon) during dust ejection, they might influence how dust is released or charged. Phaethon's perihelion is very close to the Sun (~0.14 AU), where plasma wave activity (including ion-acoustic or high-frequency whistler/electrostatic waves) is intense [8]. The research notes suggest that **"ion-acoustic waves or whistler modes in the kHz range"** might provide resonant excitation of Phaethon's surface material [9] – for instance, by vibrating or electrostatically agitating the dust. If certain high-frequency plasma waves match mechanical frequencies of porous regolith, they could help liberate dust grains. This is a different kind of resonance (between waves and *material* frequencies) but could lead to dust release in bursts or at particular phases of a wave cycle [10] [9]. In principle, such processes might produce **discrete clumps or "quantized" ejection bursts** of meteoroids.

Once in space, the dust grains (charged by solar UV and plasma) could interact with plasma waves. Although whistlers at 100 Hz are too fast for heavy grains, lower-frequency plasma oscillations (e.g. **ion**

acoustic waves or dust-acoustic waves) could affect grain dynamics. The **slow magnetosonic mode** itself is a low-frequency compressive wave – essentially a **"plasma slow sound"** which, as discussed above, might act to slow down the dust. If meteoroids travel faster than this slow wave speed, they could excite waves (analogous to a supersonic object generating a shock) and experience enhanced drag, whereas at the resonant speed (~35 km/s) the coupling might peak and constrain their velocity [3]. In this sense, the **35 km/s velocity can be viewed as a resonant condition** where the meteoroids and a natural plasma wave mode move together. Any faster, and the meteoroids outrun the wave (entering a "super-magnetosonic" regime) which could be unstable or quickly decelerated; any slower, and perhaps they get accelerated by plasma disturbances towards this equilibrium speed. This concept is still **hypothetical**, but it illustrates how plasma wave frequencies/velocities might map onto meteor stream behavior.

In summary, **whistler-mode waves (~100 Hz)** are indeed present in the solar wind [5], but their direct role in organizing the Geminid stream into spatially *quantized* structures is not evidenced in the literature. It's more plausible that **larger-scale resonances** (like the slow MHD mode at ~35 km/s) or **gravitational dynamics** (see below) set the structure. The idea of "quantization" might be better interpreted as the stream having distinct components or preferred states, possibly linked to resonant interactions – either with plasma or with gravitational perturbations.

Meteor Radar Observations: Velocity Gaps or Bimodality?

To test for any **"gaps" or multi-modal structure** in the Geminid meteoroid velocities, we can look at observational data from meteor radars. **Radar observations** (e.g. CMOR – the Canadian Meteor Orbit Radar, and MAARSY or other high-power large-aperture radars) measure meteor speeds by detecting ionized meteor trails (head-echoes and specular trails). These measurements can reveal the **distribution of meteor velocities** for a given shower. If the Geminid stream were somehow split into distinct velocity components (or if certain speeds were absent due to a resonant effect), it might show up as a **non-single-peaked distribution** or as **"gaps"** in the histogram of meteor speeds.

So far, radar studies indicate that the **Geminids have a fairly narrow speed distribution centered around ~34–35 km/s**, consistent with the stream's known geocentric velocity. For example, Younger et al. (2009) analyzed two years of Geminid radar detections and found the distribution of geocentric speeds to be approximately **Gaussian, peaked at the expected value (~35 km/s)** [11] [12]. Figure 2 of their study shows the Geminid velocity histogram, which is well-fit by a single Gaussian curve around the IAU-cataloged Geminid speed (after correcting for atmospheric deceleration) [13]. There is **no obvious secondary peak or gap** in that distribution – essentially all detected Geminid meteors cluster around the one characteristic velocity (with a spread of a few km/s due to measurement uncertainties and deceleration effects). In other words, **the radar-measured speed distribution appears unimodal (single-peaked)** for the Geminids [11]. This suggests that, at least in the atmosphere, the incoming Geminid meteoroids have **one dominant velocity mode (~35 km/s)** rather than two distinct groups.

However, when we consider the **temporal activity profile** of the Geminid stream (the meteor rates as a function of time or solar longitude), there is evidence of a **bimodal structure**. Multiple observations (visual, video, and radar) have noted that the Geminid shower's activity curve has **two peaks** – a main maximum and a secondary enhancement. For instance, analysis of 2013 Geminid impacts on the Moon by NASA's LADEE mission (LDEX dust detector) revealed **two distinct peaks in dust flux** as the Moon passed through the stream [14]. These two peaks in the lunar dust data coincided with subtle features in radar observations of the Geminids on Earth, suggesting the stream has a **double-peaked density structure** in space [14]. This **"bimodal activity profile"** has been discussed in earlier works as well (e.g. visual/radar observations from the 1980s and 2000s) and is thought to reflect the stream's formation history [15]. In particular, the two peaks could correspond to meteoroids from two different perihelion passages of the parent object or fragments from two discrete ejection events. **Galina Ryabova (2001)** modeled the Geminid stream and noted **"the existence of two maxima of the Geminid meteor stream activity"** in both observations and simulations [16]. So the term *bimodality* here refers to **two peaks in meteor counts vs. time**, rather than two distinct speeds. All meteoroids in both peaks still travel at roughly the same velocity (~35 km/s) when they hit Earth; they're just arriving in two separate clumps in space.

As for **"quantization"** or **gaps** in the stream, one mechanism that can produce gaps in meteoroid distributions is **gravitational mean-motion resonances (MMRs)** with planets. Over time, small orbital perturbations by planets (especially Jupiter) can cause meteoroids to cluster or disperse at certain orbital periods. It is known from celestial mechanics that **MMRs can scatter particles and create under-densities (gaps)**, analogous to how Jupiter's resonances create Kirkwood gaps in the asteroid belt [17]. Recent modeling of the Geminid meteoroid stream indeed found evidence for several Jovian mean-motion resonances affecting Geminid particles (in the mass range 3×10⁻

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