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MODELS

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VERTICAL TRANSPORT AND SOURCES IN FLUX MODELS

Gregory H. Canavan

Vertical transport in flux models is examined and shown to reproduce expected limits for densities and fluxes. Disparities with catalog distributions are derived and inverted to find the sources required to rectify them.

Vertical transport in flux models is examined, solved analytically for steady state solutions, and shown to reproduce expected limits for fluxes and densities at altitudes below 1,000 km where transport is significant. Below about 800 km, the densities, fluxes, and limiting expressions inferred from the steady-state approximation are in good agreement with those from flux models. However, that does not mean the inferred densities agrees with observations. Some of that discrepancy is due to the large, intact objects, which are not treated here; some may be due to model assumptions; the rest could be due to additional sources not treated.

The vertical transport model can also be used to infer the sources required to rectify differing density profiles. The difference source inferred peaks between about 550 km and 350 km. Its integral over altitude gives a number of fragments per year comparable to the number of large and mission related objects ignored in these calculations. Atmospheric scale height and drag are important in the flux calculations and the catalog, but the inferred densities have about the same scale height as the catalog below about 450 km, where much of the inferred source is located. To resolve this factor, it appears necessary to consider the contribution of large, intact objects and other items in the catalog.

Vertical transport in flux models is discussed in a companion paper, which treats the general time dependent case.¹ The principal interest in this note is in time independent solutions

$$F_z = F_{z+1} + S_z, \quad (1)$$

$$N_z = (S_z + F_{z+1})T_z, \quad (2)$$

where N_z is the density of particles at altitude z , F_z is their vertical flux at that altitude, T_z is their decay time, and S is their source. As the vertical transport of large, intact objects is small, the only densities and fluxes treated here are those of the fragments, which are described by a single eccentricity in a mean decay time model. As steady state is assumed, fragments cannot accumulate at any altitude. Thus, Eq. (1) dictates that any fragments produced at each altitude just join the flux towards the ground. Equation (2) indicates that the number density is in equilibrium between the sources, fluxes, and decay. Under the approximation that the flux is proportional to the density,

$$F_z = N_z/T_z, \quad (3)$$

Eqs. (1) and (2) reduce to

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$$N_Z = (S_Z + N_{Z+1}/T_{Z+1})T_Z, \quad (4)$$

which can be integrated down from altitudes where N_Z is small, to determine N_Z at lower altitudes. The result is shown in Fig. 1, which compares N calculated with Eq. (4) to the result of a flux model calculation that integrates the time dependent equations forward from zero fragments 35 years ago with historical launch and fragmentation rates. The N_Z from Eq. (4) is an order of magnitude larger than the N from the flux calculation at altitudes above 1,000 km due to the time dependent terms that are neglected in N_Z . By about 800 km, however, the two curves converge; the density and flux are essentially time independent and related by Eq. (4) there.

Figure 2 shows the vertical variation of the sources and vertical fluxes from the flux calculations, together with the ratio F_{Z+1}/S_Z , which measures their relative contribution to N_Z . Above 800 km, the sources are much larger than the fluxes, which are limited by the long relaxation times. By 750 km, the ratio F_{Z+1}/S_Z is about unity. At lower altitudes, the divergence of the flux is a larger effect than the sources in determining the variation of N_Z with z . By 450 km, the flux is about a factor of five larger than the source, so Eq. (4) reduces to roughly

$$N_Z/N_{Z+1} \approx T_Z/T_{Z+1}, \quad (5)$$

producing the exponential decay shown in Fig. 1. Thus, the vertical transport model used does reproduce the expected limiting forms of the vertical fluxes as well as the behavior of the densities observed in flux model calculations.

Catalog comparison. However, agreement between the density inferred from Eq. (4) with that calculated by the flux model does not necessarily imply agreement with observations. Figure 3 compares the density inferred from Eq. (4) with the catalog densities. The large differences above 1,000 km are from the neglect of time dependencies, as noted above. But the inferred density falls much more rapidly below there, crossing the catalog at about 800 km and falling an order of magnitude below it by 450 km. While some of that discrepancy is due to the large, intact objects, which are not treated here, the rest is due to assumptions in the model or additional sources. The discussion above indicates that the vertical transport reproduces the expected limiting as well as the behavior of the densities observed in flux model calculations. Thus, it is useful to examine the sources required to produce the observed differences.

Inferred sources. The vertical transport model can also be used to infer the sources required to rectify differing density profiles by solving Eq. (4) for

$$S_Z = N_Z/T_Z - N_{Z+1}/T_{Z+1}. \quad (6)$$

Thus, if the difference between the two density profiles is

$$\Delta N_Z = N_Z - N'_Z, \quad (7)$$

the difference source that would be required to bring the two density profiles into agreement is

$$\Delta S_Z = \Delta N_Z/T_Z - \Delta N_{Z+1}/T_{Z+1} = \Delta F_Z - \Delta F_{Z+1}. \quad (8)$$

Fig. 4 shows which is shown Figure 3 shows ΔN_z , ΔF_z , and ΔS_z required to bring the results of the flux model into agreement with the catalog. The difference density $\Delta N = N_{\text{catalog}} - N_{\text{flux}}$ is negative above 1,500 km, because the fragment source used in the flux calculation is too high there. The spike at 1,450 km is an artifact of the neglect of the large, intact objects, which make up much of the density at that altitude. That is also the reason for the spike at 950 km.

The gentle hump below about 850 km is not all due to large objects; it represents the input to the difference source calculation. The differential flux is small above 850 km due to the long decay times there. By 600 km, it reaches about 200 fragments/year, and by 250 km, it reaches almost 1,600 fragments per year. The difference of this flux in Eq. (8) then gives the difference sources shown, which rise with the difference flux to about 550 km, drop away, peak at about 600 objects per year at 350 km, and then fall rapidly towards zero. The integral of this difference source over all altitudes gives a total of about 1,600 fragments per year, which for linear growth over 35 years would give a total of $\approx 0.5 \times 1,600/\text{yr} \times 35 \text{ yr} \approx 28,000$, which is about twice the number of large and mission related objects ignored in the calculations above, which treat only fragments. While the source is large, it is estimated for small fragments at low altitudes, which would not survive long.

An alternative that could be explored in the same way is the effect of the difference in scale heights in the flux calculations and in the catalog. Figure 1 shows that the scale height plays a dominant role in vertical fluxes from flux calculations at altitudes below about 800 km. However, Fig. 3 suggests that the flux calculations use about the same scale height below about 450 km, where much of the inferred source is located. At the level of determining the last factor of two, it is necessary to consider both the contribution of the large, intact objects, which is subtractive, and the rest of the items in the catalog, which require a detailed treatment of them.

Summary and conclusions. Vertical transport can be solved analytically in flux models in steady state, which is roughly the condition at altitudes below 1,000 km where transport is significant. is shown to reproduce expected limits for fluxes and densities. Disparities with known distributions are inverted to find the sources that rectify them. Below about 800 km, the densities, fluxes, and limiting expressions inferred from the steady-state approximation are in good agreement with those from flux models. However, that does not mean the inferred densities agrees with observations. Some of that discrepancy is due to the large, intact objects, and some may be due to model assumptions, the rest could be due to additional sources.

The vertical transport model can also be used to infer the sources required to rectify differing density profiles. The difference source inferred rise with the difference flux to about 550 km, peak at about 600 objects per year at 350 km, and fall rapidly towards zero at lower altitudes. Its integral over altitude gives a number of fragments per year comparable to the number of large and mission related objects ignored in these calculations, which treat only

fragments. Although atmospheric scale height and drag are important in the flux calculations and the catalog, the flux calculations produce about the same scale height as the catalog below about 450 km, which is where much of the inferred source is located. To resolve the last factor of two in this comparison, it appears necessary to consider both the contribution of the large, intact objects, which is subtractive, and the rest of the items in the catalog, which require a detailed treatment. The discrepancy is significant at the altitudes of manned space operations, but not at higher altitudes where impact hazard and cascading are more of a concern.

Reference

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1. G. Canavan, "Estimates of Current Debris Fluxes," Los Alamos report, August 1996.

Fig. 1. Comparison of quasi-steady density and time-dependent density vs altitude.

Fig. 2. Sources, fluxes, and ratios as functions of altitude.

Fig. 3. Fragment density from flux calculation and catalog versus altitude.

Fig. 4. Difference density, flux, and source as functions of altitude.