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GLOBAL CHANGE IN THE THERMOSPHERE: COMPELLING EVIDENCE OF A SECULAR DECREASE IN DENSITY

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Introduction: The Naval Research Laboratory has pioneered a fast and accurate method of processing standard data on spacecraft orbits (“two-line element sets” or TLEs) to determine the total mass density of the highest layer of the Earth’s atmosphere, known as the thermosphere.¹ Although the atmosphere is extremely thin in this region (the air at the Earth’s surface is a trillion times thicker), it is enough to exert a drag force on satellites, causing their orbits to decay slowly and ultimately resulting in a fiery disintegration at lower altitudes. The Naval Space Surveillance System (NAVSPASUR) radar fence, operated from the Naval Surface Warfare Center in Dahlgren, Virginia, provides key observation sets from which the trajectories of Earth-orbiting objects are reduced to TLEs. The resulting Space Object Catalog presently allows the U.S. Space Command to track and predict the locations of more than 12,000 objects, most of which are in low-Earth orbit (LEO). This archive extends back 40 years and represents an unexploited source of global information on the thermosphere. The thermosphere exerts drag on LEO objects, reducing their useful lifetimes, orbital predictability, and safety.

Starshine Satellites: The power of the new method became clear when the NRL group retrieved density values from orbits of the Starshine satellites (1, 2, and 3) that flew during the years 1999-2003, the maximum of the 11-year solar cycle.² NRL’s Spacecraft Engineering Department (Code 8200) built the Starshine spacecraft, which were covered with hundreds of mirrors polished by students around the world. The spherical shape of these objects made them invaluable as drag and radar calibration objects. The thermospheric mass density values derived from the Starshine orbits agree well with NRL’s empirical atmospheric model, NRLMSISE-00, the space research community standard for estimating the properties of the thermosphere (Fig. 1). This accord across three different orbits and distinct levels of solar activity verifies the new method. The orbits and the model both show density fluctuations that are driven mainly by changes

in the Sun’s extreme ultraviolet radiation. More importantly, the TLE-based densities represent the true thermospheric state for a given day and year—superior to the model.

Armed with this new tool and with TLEs of spacecraft remaining in orbit over several decades, NRL attacked one of the central issues of modern-day geophysics—long-term, global atmospheric change. The study shows that the highest layers of the Earth’s atmosphere are cooling and contracting, most likely in response to increasing levels of greenhouse gases.³ The average density of the thermosphere has decreased by about 10% during the past 35 years, a contraction that could cause longer orbital lifetimes for both satellites and the hazardous space debris that threatens them.

Figure 2 shows the trends derived from orbital tracking data on 25 long-lived objects whose closest approach to the Earth lies within 200 to 800 km (124 to 497 miles). For comparison, the Space Shuttle typically orbits at 300 to 450 km (186 to 279 miles), and the International Space Station maintains an altitude of about 400 km (248 miles). By analyzing changes in the orbits of the selected objects, the NRL team derived the yearly average density encountered by each object over the period 1966-2001. After adjusting for the larger-amplitude 11-year density cycles driven by solar activity and for other factors, the data from every object indicated a long-term decline in the density of the thermosphere.

Density Changes: Such a density decrease had been predicted by theoretical simulations of the upper atmosphere’s response to increasing carbon dioxide and other greenhouse gases. In the troposphere (the lowest layer of the atmosphere), greenhouse gases trap infrared radiation, causing the well-known “global warming” effect. In contrast, higher up (above 12 km, or 7.5 miles), these gases enhance the ability of the atmosphere to radiate heat to space, tending toward cooling. As the amount of carbon dioxide increases, the upper atmosphere becomes cooler and contracts, bringing lower-density gas to lower heights. Consequently, the average density at a given height decreases. Because each layer of the atmosphere rests on the layers below it, small changes at lower altitudes become amplified at higher altitudes. According to Fig. 2, the observed decrease in density depends on height in the same way as predicted by the theoretical simulations. This suggests that greenhouse gases are a likely source of the change. An extreme example of the greenhouse gas effect can be found on Venus, whose atmosphere is 96% carbon dioxide (compared to trace amounts in the Earth’s atmosphere), resulting in a very

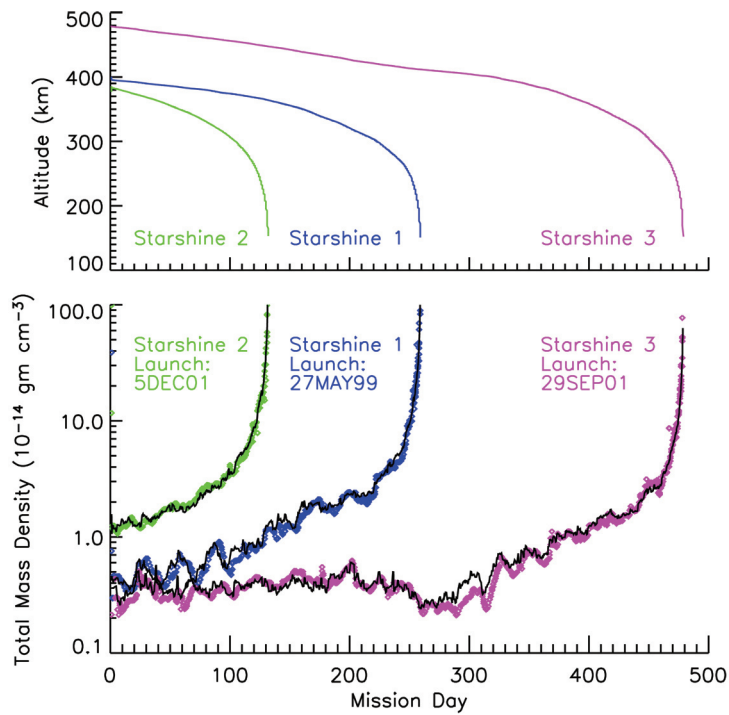
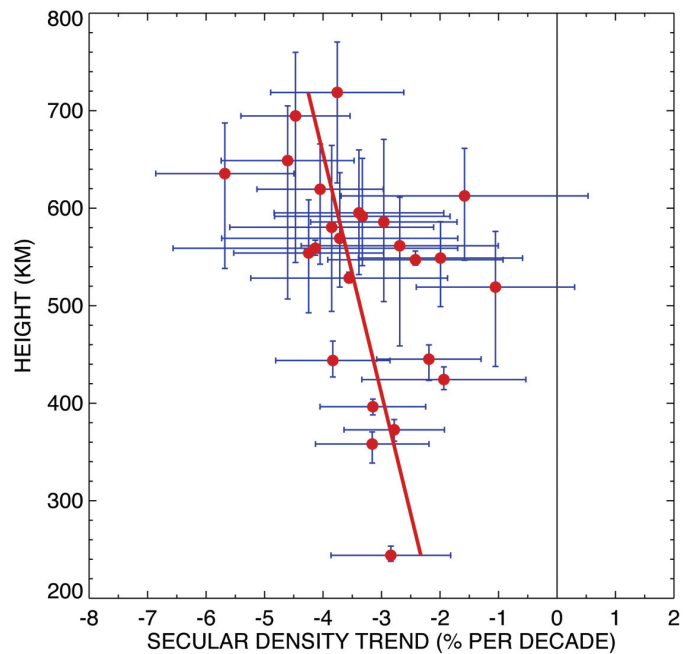


FIGURE 1

Shown throughout each Starshine mission are (top) the altitude of the satellite vs mission day and (bottom) corresponding total mass density values. In the latter, the colored symbols show the TLE-based density values; the black lines show the corresponding values from NRLMSISE-00.

FIGURE 2

Summary of secular density trends derived from 25 objects, as a function of drag-weighted average height (near perigee). The horizontal bars indicate the 1σ uncertainty in the trends, and the vertical bars denote the range of heights covered by each object.



hot lower atmosphere (800 °F, 427 °C) and a very cold and compact upper atmosphere.

Conclusions: Based on the NRL analysis and projections of carbon dioxide levels in the atmosphere, the density at thermospheric heights may be halved by the year 2100. This change may have mixed impacts: while satellites will stay in orbit longer, saving fuel, so will damaging spacecraft debris, potentially increasing the frequency of collisions.

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