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Investigation of an Unusual Thin Layer Descending Through the Upper Stratosphere

Houston D. Bentley

Utah State University

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Houston D. Bentley, Ben P. Cannon, Vince B. Wickwar
Department of Physics, Utah State University, Logan UT 84322

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Lidar observations on the night of 19-20 February 2004 at Logan, Utah (41.74 N, 111.81 W) revealed a strange thin layer which descended from roughly 55 km to 30 km over seven hours. Approximations are made for the dimensions and descent rate of the layer. Although the particle radius and density are unknown, a range can be determined from the descent rate and reference to the sizes of known particles. Several possible sources for the layer are explored, concluding that an object entering the Earth's atmosphere was the most probable cause.

I. INTRODUCTION

Aerosols are small particles suspended in the Earth's atmosphere. When these particles are large enough, light is scattered as it passes through an aerosol layer. This scattering is observable as haze or the red color of sunsets. Aerosols are always present in the atmosphere, but they typically exist only at altitudes below 30 km.[1] Naturally occurring aerosols are commonly formed when particles are ejected from a volcanic eruption into the atmosphere. Also, dust from desert wind storms can be blown into the atmosphere, causing aerosol layers to form. Man-made aerosols are mainly produced from the burning of coal and oil. Meteoroids and meteoric dust are other sources of particles that can be suspended in the atmosphere. Meteor influx to earth is about 1.6×10^4 tonnes per year.[2] From an analysis done by Hunten, et al. it was indicated that in the upper stratosphere meteoric dust could be the dominant aerosol condensation nucleus.[3]

On the night of 19- 20 February 2004, a thin aerosol layer was detected by the Rayleigh LIDAR System (RLS) at Utah State University. The layer descended from roughly 55 km to 30 km over seven hours of observation (Fig. 1). In the decade of operation prior to this night, no other LIDAR returns resembling these recordings are known. Reports of similar observations are scarce, but a few cases are in the literature and will be discussed below. Reported here are the efforts to describe some of the physical characteristics and possible sources of the strange layer.

II. INSTRUMENTATION AND OBSERVATION

The RSL at USU's Center for Atmospheric and Space Sciences is an instrument used for making observations in the upper stratosphere and mesosphere. A high-power Nd:YAG laser is used to send 30 pulses per second straight up into the atmosphere. As the emitted light encounters particles, photons are scattered. Some of these photons are scattered back towards the Earth, where they are collected by a 44-cm diameter telescope. A sensitive photomultiplier tube (PMT) detector is then

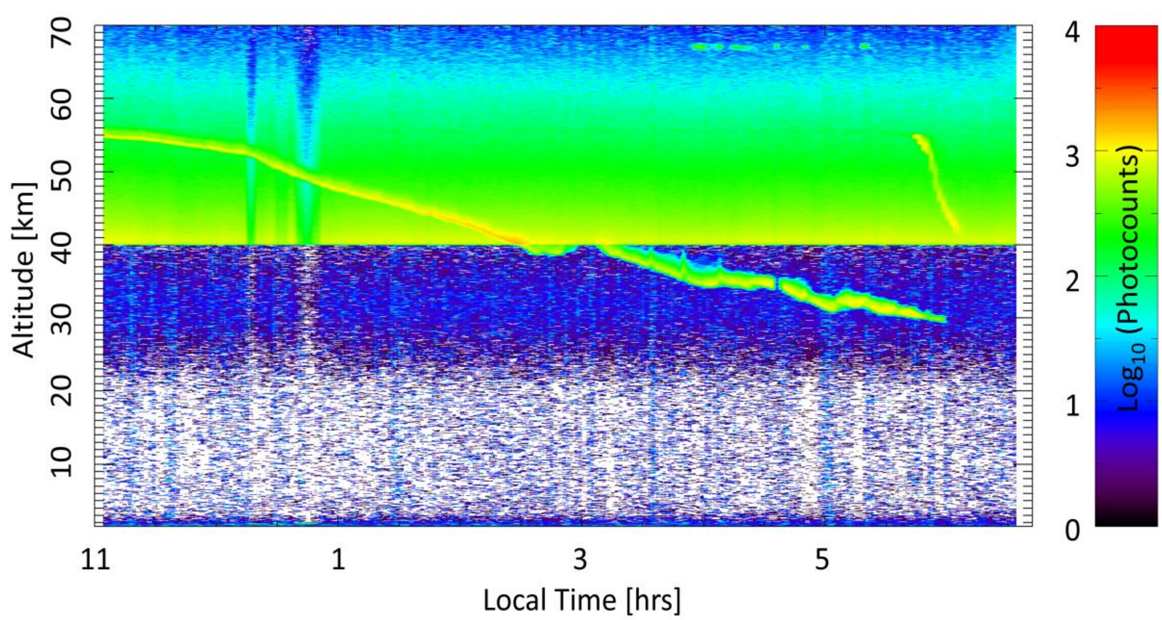

Fig. 1. Lidar return for the night of February 19-20, 2004. At 40 km, the gain on the photomultiplier tube detector is increased, preventing intense signals from overwhelming the system. The unusual layer persistently stands out from the background throughout its descent. The sharp decrease in intensity at 40 km corresponds to a manual change of gain of the apparatus to protect the sensitive detector.

used to measure the photons backscattered from the atmospheric molecules and/or aerosols. Return signals are collected at two-minute intervals at a vertical resolution of 37.5 meters. Vertical profiles can be constructed to show photon counts at each altitude, as shown in Fig. 2. Fig.1 is a compilation of each profile for the night of interest with a log scale color code representing the number of photons detected.

In investigating the peculiar LIDAR return, a preliminary concern was the reality of the signal. Electrical interference from nearby equipment could possibly cause similar returns. Initially, the observer on duty suspected an apparatus malfunction. The shutter on the detector was closed and opened several times, with the signal disappearing whenever the path of light was blocked. This showed that the detector was properly functioning.

Further substantiation of the signal comes from close inspection of the profiles. In Fig. 1, three columns of lower intensity are seen between 12:00 and 1:00 a.m. local time. At the base of each column is a very thin green layer. These columns are frequently returned by LIDAR detection and correspond to clouds passing over the observatory. The clouds act as a filter, decreasing the entire signal above them. Fig. 4 shows the passing cloud at approximately 2 km, and the reduced signal for the rest of the profile. The aerosol layer is more pronounced against the filtered background scattering, but the peak intensity is reduced as well, dropping by nearly 17%. More clouds are seen near 5:00 a.m. with similar results. Thus, the signal is presumed to be authentic.

III. CHARACTERISTICS OF THE AEROSOL LAYER

A primary result of this research has been the determination of various physical features of the observed aerosol. Included are thickness, horizontal extent, and descent rate of the layer.

Looking at Fig. 1, one can easily say that the layer is quite thin. More quantitatively, the thickness, or vertical extent, can be estimated

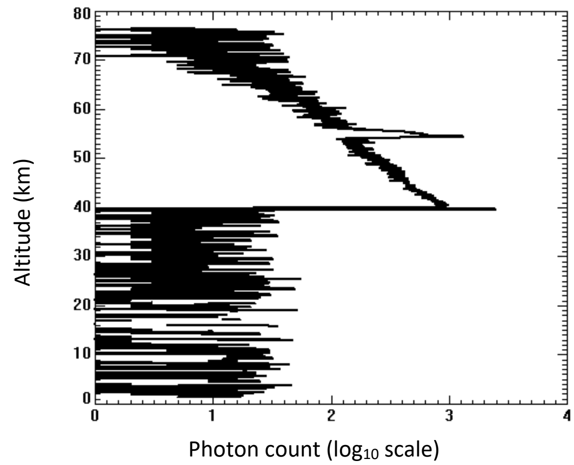

Fig. 2. Vertical profile of LIDAR return at 11:20 p.m., 19 Feb. 2004. The unusual layer is seen at 55 km. The signal drops off below 40 km shows the change of gain.

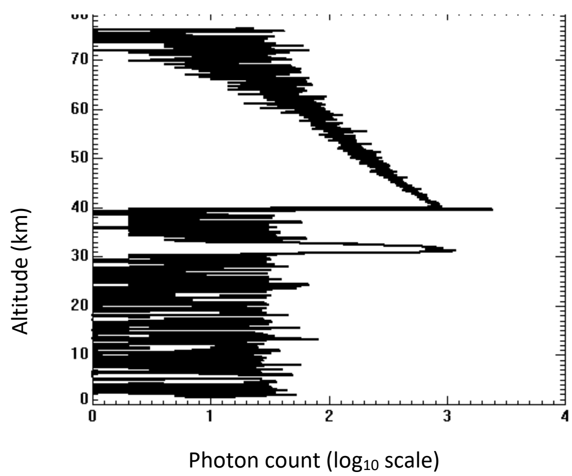

Fig. 3. Vertical profile at 5:00 a.m., 20 Feb. 2004. The layer has descended to 31 km.

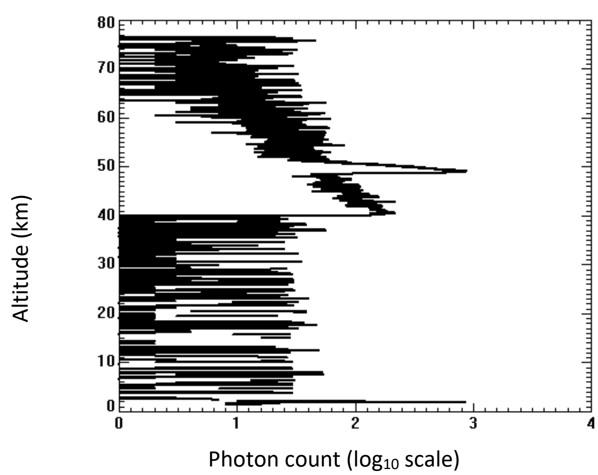

Fig. 4. Vertical profile at 12:40 a.m., 20 Feb. 2004. A passing cloud at approximately 2 km filters the entire profile.

by measuring the full width at half of the max intensity. This was done to profiles at nineteen times throughout the night when the peak was sufficiently distant from the gain change to be distinguishable. These values ranged from one to three kilometers and the average thickness was 1.6 km with a standard deviation 0.5 km. The layer did not noticeably spread out vertically, as there was no apparent time dependent trend in the thickness.

The LIDAR system is stationary, taking measurements only directly above it. Therefore, to estimate the horizontal extent of the layer, one can multiply the duration of observation by the rate of motion. The primary force acting on aerosols is typically in the form of wind. The most recent and complete model for wind speed is the Horizontal Wind Model 07 (HWM07) which was built using measurements from satellite, rocket, and ground-based observations over the past fifty years.[4] Using this as our resource, it was determined that, in general, the direction of winds at the level of the unusual layer was eastward. In fact, the wind vector never varied more than 13 degrees north or south of directly east, except when wind speed dropped to a fraction of the mean speed (Table 1). The mean wind speed was determined at the altitude of the layer every thirty minutes. By summation of the products of the speed and time intervals, an approximation of winds experienced by the layer throughout its descent was made. Assuming the aerosol particles were being carried with the wind, the observed portion of the layer spanned roughly 834 km. It must be noted, of course, that this value is only an approximation of what the extent would be given normal atmospheric conditions. The model only gives time averaged values based on geographic location, altitude, and time of year.

To measure the descent rate of the aerosol layer, peak intensity was plotted as a function of time. Individual profiles from every twenty minutes were used so the altitude of the peak could be more precisely determined. Fig. 5 shows the trend, which fits very well with the included linear regression. The slope of the regression line gives a good approximation of how fast the layer descended. The descent rate, then, was a relatively constant 3.96 km per hour, or 1.1 m/s.

TABLE I. Wind influence on the unusual layer

Local time	Altitude (km)	Wind speed (m/s)	Wind direction (˚counterclock-wise from eastward)
11:00 p.m.	55	46.17	347.9
11:30 p.m.	54	47.11	350.6
12:00 a.m.	53	47.88	354.5
12:30 a.m.	50	47.79	5.3
1:00 a.m.	47	46.66	7.7
1:30 a.m.	45	44.29	5.9
2:00 a.m.	43	40.05	3.0
2:30 a.m.	41	34.64	359.9
3:00 a.m.	40	31.77	358.4
3:30 a.m.	38	26.06	356.5
4:00 a.m.	36	20.35	355.1
4:30 a.m.	34	14.64	352.1
5:00 a.m.	32	9.55	344.1
5:30 a.m.	30	6.21	329.3

Several approaches have been used to describe the relationship between descent rate and particle size. Kasten[3] modeled the descent rate of spherical particles with mass density 1 gm cm^{-3} based on particle radius. From Kasten's tables, and assuming the descent rate given above is reasonable, the cloud in question must have been composed of particles over 10 μm in radius at the beginning of observation. If the mass density were greater than 1 gm cm^{-3}, this radius would be smaller. As nothing is known about the mass density of the particles in the unusual cloud, Kasten's model merely provides a vague estimate of particle size. There is however a relation describing the particle descent rate in terms of the mass density and radius:

$$v_p = \frac{2\rho_a g}{9\eta} r_p^2$$

where v_p is the descent rate, ρ_a is the mass density, g is the acceleration due to gravity, η is the dynamic viscosity of the atmosphere the layer is traveling through, and r_p is the radius of the particles[5]. This relation is valid under the stipulation that $\rho/\rho_a < 10^{-3}$, where ρ is the

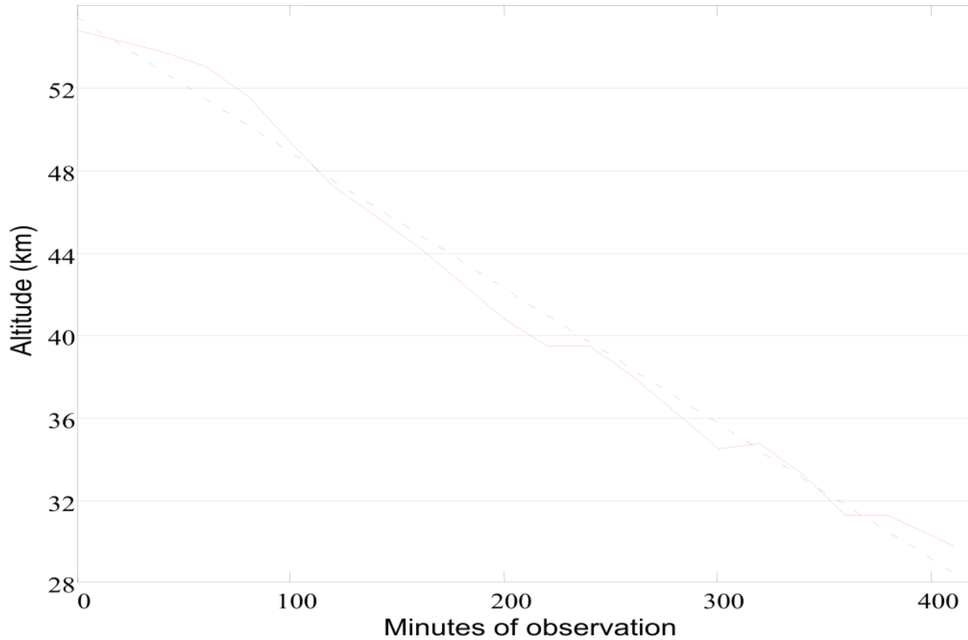

Fig. 5. Descent rate of the aerosol layer. Plotting the altitude of the peak intensity verse time gives a nearly linear result. The linear regression has a R^2 value of 0.988.

mass density of the gas the particles are suspended in.

The dynamic viscosity is purely a temperature dependent variable. The relation between dynamic viscosity and temperature is expressed as

$$\eta = \frac{\beta * T^{3/2}}{T + S}$$

Where β is a constant equal to 1.458×10^{-6} kg/(s*m*$K^{1/2}$) and S is the Sutherland constant, equal to 110.4 K. This expression fails for very high and very low temperatures and at high altitudes greater than 86 km. [US standard]

Using the temperatures from MERRA-2 of that night, an average dynamic viscosity of $9.9\times10^{-7} \pm 2.3\times10^{-8}$ kg/m*s was obtained. Under the assumption that the particles are at least 10 µm in radius and given that meteoric dust is known to have radii between 10 µm and 50 µm [James], a mass density range between 5 gm/cm^3 and 0.2 gm/cm^3 is calculated. This range covers most of the common aerosols. Sulphate particles, for instance, have a mass density of about 1.8 gm/cm^3 and have a radius of 1.7 µm [Kasten].

V. POSSIBLE SOURCES OF THE LAYER

Volcanic activity is responsible for the bulk of naturally occurring aerosols. When a volcano erupts, huge amounts of sulfur are injected into the atmosphere. The 1991 eruption of Mt. Pinatubo in the Philippines was the second largest eruption in the twentieth century and provided researchers with an excellent opportunity to study aerosols in many ways. The NOAA/11 and SAGE II satellites were used to monitor the global dispersion of the aerosol cloud.[9,10] Numerous land-based studies were made,[11] and even research vessels equipped with lidar detectors were used to make mobile, sea-based measurements.[12] From these studies it was found that the sulfuric aerosols from the Mt. Pinatubo eruption gradually dispersed, covering 42% of the Earth's surface two months after being introduced into the stratosphere. The clouds existed just below 30 km shortly after being produced, and then descended to as low as 16 km over a period of six months. Remnants of volcanic aerosols are known to persist in the atmosphere for up to five years.

There were no major volcanic eruptions in the few years prior to the night when the strange aerosol cloud was observed over Logan. Smaller eruptions happened commonly worldwide, but ejecta being shot much over six kilometers high was a much rarer occurrence. The strange cloud detected over Logan did not follow the slow descent and dispersion patterns typical of volcanic aerosols. These differences and the lack of a major eruption close to the date of observation make it seem unlikely that the layer of interest could have been caused by volcanic activity.

The possibility of the odd layer being a weather feature was also investigated. Noctilucent clouds reflect sunlight long after sunset and long before sunrise because of their high altitudes. Investigation was made into the possibility of the unusual LIDAR reading being caused by noctilucent clouds, or by similar polar stratospheric clouds. These rare formations generally occur at altitudes of 20 to 30 km and are most prevalent between latitudes of 50° and 65°. Cloud formation at these altitudes requires temperatures below -78° C, and therefore these clouds are usually only observed during the winter months. Several studies described in the literature focus on noctilucent or polar stratospheric clouds that were observed outside of the conditions at which they are normally seen. [13,14,15] These clouds appear to have been somewhat similar in form to the cloud observed above Logan, but they didn't behave like it. These unique weather formations can persist for months, only losing about 10 km of altitude. The unusual layer, however, steadily descended through much of the atmosphere in just a few hours. The cloud is therefore not believed to have been a feature of the weather.

Aerosol clouds can also form as objects pass through the atmosphere. As a rocket travels through the atmosphere, large quantities of water particles are produced as exhaust, and clouds of ice crystals are formed along the flight path. Similar to volcanic aerosols, these clouds can disperse rapidly to other regions of the world. For example, a cloud observed over California in April 1997 was linked to the launch of a Russian Soyuz rocket 12 days earlier.[16] This cloud had reportedly spread to 180 km in horizontal extent and descended to an altitude of 20 km. Another study has focused on rocket aerosols found at higher altitudes only minutes after launch. [17]

In the two weeks prior to the appearance of the strange layer above Logan, there were three major launches of spacecraft. An Atlas 2AS rocket and a Titan 402B rocket were launched from Cape Canaveral on the 5th and 14th of February 2004, respectively. it is unlikely that aerosols from these launches were detected due to the exhaust being blown over the Atlantic Ocean and due to turbulent mixing with the atmospheric gas would not have been detectable. On the 18th of the same month, a Russian Molniya-M rocket was launched from Plesetsk, Russia.[18] It is possible that the RLS could have detected aerosol clouds from this launch. However, the Layer's rapid descent and no indication of settling, is inconsistent with the behavior of other rocket aerosols, which gradually dissipate after settling at a given altitude. This casts doubt on attributing the strange cloud to exhaust from a space launch.

Aerosols can form not only as objects escape the atmosphere, but as they enter it as well. Meteors, space debris, and decommissioned spacecraft usually burn up or break apart as they reenter the atmosphere, never hitting the Earth's surface. The object may be visible as a "shooting star", with larger particles forming the long tail behind the main body. As small particles are ripped from the object, a cloud is often formed. Additionally, the Earth occasionally passes through dust left behind comets. This dust can be captured by the gravity of the Earth and form aerosols.[19]

No major meteor showers or significant single meteor events are known to have happened during February of 2004.[21] While celestial events of this nature are of widespread interest, it is conceivable that many objects enter the atmosphere undetected. Likewise, there is the possibility of classified military exercises that could produce the observed layer.

Only one reentry event was scheduled to occur close to the date of the strange cloud over Logan. A Centaur rocket body reentered the atmosphere on 12 February, 2004.[20] As this was over a week before the cloud was detected above Logan, -debris from this reentry would probably have a rate of descent lower than that of the observed cloud at the time of observation.

VI. CONCLUSION

It is not uncommon to detect strange clouds like the one detected over Logan. Other instances of anomalous layers being detect include the layer observed in Aberstwyth, Wales in 1983,[22] the layer detected over Sweden in 1998,[14] and the layer detected in the artic in November of 2001.[23]

Several potential sources have been deemed less likely, such as volcanic eruptions, unique weather features, and rocket exhaust. A heretofore unknown meteor entry, meteoric dust layer or undisclosed space debris reentry seem to be the most plausible explanation for the unusual layer. A major concern was if the layer was real and not caused by an electrical malfunction. The filtering caused by the clouds that passed through the laser substantiates the layer's authenticity. An issue not investigated thoroughly in this study was the appearance of a second strange layer near 70 km around 4 AM and a third layer just as the signal from the layer of interest was fading out around 6 AM. This third cloud is seen in Fig. 1 as the very rapidly falling yellow streak at approximately 4:00 a.m. The appearance of multiple layers supports the possibility of an Meteoroid or spacecraft breaking apart as it descends. This question would benefit from further research into behavior of aerosols produced by objects entering the atmosphere.

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REFERENCES

[1]R. C. Whitten, (ed.) The Stratospheric Aerosol Layer (Springer, Berlin, 1982).

[2] Hughes, D. W., Meteors, in Cosmic Dust, edited by J. McDonnell, chap. 3, John Wiley, N.Y., 1978

[3] Hunten, D. M., R. P. Turco, and O. B. Toon, Smoke and dust particles of meteoric origin in the mesosphere and stratosphere, or. Atmos. Sci., 37, 1342-1357, 1980.

[4]D. P. Drob, et al., "An empirical model of the Earth's horizontal wind fields: HWM07," J. Geophys. Res., **113**, (2008).

[5]Chernogor, L. F. 2017. "Atmospheric Effects of the Gas–Dust Plume of the Chelyabinsk Meteoroid of 2013." Izvestiya, Atmospheric and Oceanic Physics 53 (3): 259–68.

[6]F. Kasten, Falling Speed of Aerosol Particles, J. Appl. Met., **7**, 944-947, (1968).

[7]U.S. standard atmosphere, 1976. (1976). Washington D.C.: National Oceanic and Atmospheric Administration National Aeronautics and Space Administration United States Air Force, p.19.

[8]James, Alexander D., Victoria L. F. Frankland, Josep M. Trigo-Rodríguez, Jacinto Alonso-Azcárate, Juan Carlos Gómez Martín, and John M. C. Plane. "Synthesis and Characterisation of Analogues for Interplanetary Dust and Meteoric Smoke Particles." Journal of Atmospheric and Solar-Terrestrial Physics, Layered Phenomena in the Mesopause Region, 162 (September 1, 2017): 178–91.

[9]L. L. Stowe, R. M. Carey, P. P. Pellegrino, "Monitoring the Mt. Pinatubo aerosol layer with NOAA/11 AVHRR data," Geophys. Res. Lett., **19**, 159-162, (1992).

[10]M. P. McCormick and R. E. Veiga, "SAGE II measurements of early Pinatubo aerosols," Geophys. Res. Lett., **19**, 155-158, (1992).

[11]S. I. Avdyushin, et al., "Spatial and temporal evolution of the optical thickness of the Pinatubo aerosol cloud in the northern hemisphere from a network of ship-borne and stationary lidars," Geophys. Res. Lett., **20**, 1963-1966, (1993).

[12]B. Nardi, et al., "2. Morphology and dynamics of the Pinatubo aerosol layer in the northern hemisphere as detected from a ship-borne lidar," Geophys. Res. Lett., **20**, 1967-1970, (1993).

[13]S. G. Warren, et al., "Noctilucent cloud observed in late April at South Pole Station: Temperature anomaly or meteoritic debris?," J. Geophys. Res., **102**, 1991-2000, (1997).

[14]J. Siebert, et. al., "A strange cloud in the Arctic summer stratosphere 1998 above Esrange (68^{o}N), Sweden," Annales Geophysicae, **18**, 505-509, (2000).

[15]C. Hinz, P. Kramer, and G. P. Konnen, “Polar Stratospheric Clouds over Western Europe,” Manuscript Weather, http://www.gunther konnen.com/downloads/2009_PSC_Weather_prepr. pdf .
[16]P. A. Newman, et. al., “Chance encounter with stratospheric kerosene rocket plume from Russia over California,” Geophys. Res. Lett., **28**, 959-962, (2001).
[17]K. H. Fricke, et. al., “Visual and lidar observation of rocket induced effects in the upper atmosphere above Andoya on 25 January 2995,” Proc. 12th ESA Symp. On European Rocket and Balloon Programmes and Related Research, European Space Agency, ESA-SP **370**, 107-112, (1995).
[18]Gunter’s Space Page, Orbital Launches of 2004, WWW page, (http://space. skyrocket.de/).
[19]G. S. Kent, M. C. W. Sandford, and W Keenleside, Laser radar observations of dust from comet Bennett, J. Atm. and Terr. Phys., **33**, 1257-1262, (1971).
[20]Center for Orbital and Reentry Debris Studies, WWW page, (http://www.reentry news.com/27719.html).
[21]J. D. Matthews, Penn State, personal communications, (Oct. 2009).
[22]L. Thomas, D. P. Wareing, and D. B. Jenkins, “Observation of a thin layer of material in the upper stratosphere,” Nature, **312**, 627-628, (13 December 1984).
[23]M. Gerding, et. al., “Observation of an unusual mid-stratospheric aerosol layer in the Arctic: possible sources and implications for polar vortex dynamics,” Annales Geophysicae, **21**, 1057-1069, (2003).