# Chance encounter with a Stratospheric Kerosene Rocket Plume from Russia over California

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Short title: CHANCE ENCOUNTER WITH A STRATOSPHERIC KEROSENE ROCKET PLUME FROM RUSSIA OVER CALIFORNIA

**Abstract.**

During a routine ER-2 aircraft high-altitude test flight on April 18 1997, an unusual aerosol cloud was detected at 20 km altitude near the California coast at about 37° N latitude. Not visually observed by the ER-2 pilot, the cloud was characterized by high concentration of soot and sulfate aerosol in a region over 100 km in horizontal extent indicating that the source of the plume was a large hydrocarbon fueled vehicle, most likely a launch vehicle powered only by rocket motors burning liquid oxygen and kerosene. Two Russian Soyuz rockets could conceivably have produced the plume. The first was launched from the Baikonur Cosmodrome, Kazakhstan on April 6; the second was launched from Plesetsk, Russia on April 9. Air parcel trajectory calculations and long-lived tracer gas concentrations in the cloud indicate that the Baikonur rocket launch is the most probable source of the plume. The parcel trajectory calculations do not unambiguously trace the transport of the Soyuz plume from Asia to North America, illustrating serious flaws in the point-to-point trajectory calculations. This chance encounter represents the only measurement of the stratospheric effects of emissions from a rocket powered exclusively with hydrocarbon fuel.

## Introduction

The effects of rocket combustion emissions on the stratosphere are a serious concern because of the potential negative impact on stratospheric ozone levels. Assessing this environmental impact has proven difficult because of limited knowledge of the emissions of the various rocket motor and propellant types, far-field chemistry and plume wake processing of those emissions, and the details of the eventual dispersion of the emissions to global scales. Initial concerns focused on chlorine emissions from solid rocket motors (SRMs). Recent attention has focused on heterogeneous reactions on the surfaces of the various aerosol emissions from rocket motors, alumina from SRMs and soot and sulfate from kerosene fueled rocket motors. The surface of each aerosol type has the potential to perturb the chemistry of the stratosphere and accelerate ozone loss [*Molina et al.*, 1997]. Calculations using a two-dimensional global transport and chemistry model by citejackman indicate that chlorine activation reactions on alumina surfaces may decrease global annually averaged ozone by approximately 0.025%, although Ross et al. [1999] suggest a much smaller loss.

Beginning in 1996, the Air Force Rocket Impacts on Stratospheric Ozone (RISO) program has carried out a series of stratospheric aircraft campaigns to characterize the emissions and plume wake chemistry of SRMs minutes to hours after launch. Successful measurements in Titan IV, Space Shuttle, and Delta II plumes have produced estimates of the $Cl_2$ and submicron alumina emission indices for large SRMs as well as showing complete removal of ozone in the plume wake during the first 60 minutes after launch. In contrast to the rapid advancement in assessing SRM emissions, little attention has been paid to liquid propellant rocket motor emissions and there have been no direct measurements in plumes from rockets powered by liquid propellant alone.

A clear need for such measurements exists. Presently, we do not understand hydrocarbon rocket motor emissions well enough to reliably predict their impact on the stratosphere in an absolute sense or in comparison with SRM emissions. Several new

heavy lift hydrocarbon fueled rockets will begin operations over the next several years and it is expected that global emissions from hydrocarbon rockets will approach those of SRMs within a decade. Prudence with respect to stratospheric impacts suggests a need for detailed assessment of hydrocarbon motor impacts which is comparable to the assessment of SRM impacts.

As part of the summer 1997 Polar Ozone Loss in the Arctic Region In Summer (POLARIS) experiment, test flights of a comprehensive ER-2 payload of instruments to measure the gas and aerosol composition of the stratosphere were flown over the central California coastal region during April, 1997. On April 18, a flight with a subset of the complete POLARIS payload was flown near 37° N and 122° W at an altitude of about 20 km. During this flight extremely large concentrations of condensation nuclei (CN) were unexpectedly detected in several well defined regions extending over 100 km horizontally. The large scale of the aerosol cloud, together with its high CN concentration, presented a conundrum with regard to identification of its source.

Recently however, this unusual aerosol cloud has been reconsidered within the context of rocket motor emissions and global scale transport of airmasses in the lower stratosphere. In this paper we briefly review the measured features of the mysterious April 18 cloud and present arguments supporting the conclusion that the origin of the cloud was a kerosene fueled rocket launched twelve days previously from a site in central Asia. We show that the characteristics of the cloud aerosol, the apparent origin of the cloud airmass, and forward and backward air parcel trajectory analyses are all consistent with this identification. We also discuss some implications of the data for stratospheric meteorological models and the assessment of the stratospheric impact of rocket emissions.

# Observations

## Meteorological Data

Four different global meteorological analyses were used in this study: (1) objective analyses obtained from the Climate Prediction Center (CPC) of the National Centers for Environmental Prediction (NCEP) [*Gelman et al.*, 1986; *Newman et al.*, 1989], (2) the NCEP/NCAR reanalysis data [Kalnay et al., 1996], (3) the Goddard Space Flight Center's (GSFC) Data Assimilation Office (DAO) GEOS-STRAT analysis [*Coy and Swinbank* 1997], and (4) the United Kingdom's Meteorological Office (UKMO) UARS stratospheric analyses [*Swinbank and O'Neill* 1994]. In addition, the ER-2 Meteorological Measurement System (MMS) [*Chan et al.*, 1990] recorded in situ pressure, temperature, winds, and aircraft position.

Comparison of winds and temperatures from the global analyses to the in situ MMS measurements shows reasonable agreement. The GEOS temperatures are about 0.6 K cooler than MMS observations at potential temperatures between 460 and 520 K (approximately 50 hPa) with an RMS deviation of 0.8 K. During the flight of April 18, 1997, the winds are weak. The average MMS observed wind over the flight track is 0.9 $ms^{-1}$ and -0.15 $ms^{-1}$ in the zonal and meridional directions, respectively. This contrasts with the GEOS wind of 0.3 and 2.1 $ms^{-1}$. The RMS difference between the GEOS and MMS winds is 2.5 and 3.1 $ms^{-1}$ in the zonal and meridional directions. Such differences are very reasonable, but we note that a consistent bias in wind speed of only 1 $ms^{-1}$ will translate into a position error of nearly 1000 km every 10 days.

## Mysterious Cloud Data

Measurements made by the ER-2 aircraft on April 18 1997 included CN concentration, aerosol sizing, aerosol collection and analysis, and $NO_y$ and $N_2O$ concentrations. In this work, we consider only the CN, collected aerosol, and $N_2O$ data

and limit the discussion to identification of the cloud source: a complete analysis of the entire data set will be the subject of a forthcoming paper. Figure 1 (a) and (b) shows CN concentration as a function of time and potential temperature, respectively, on April 18 from the University of Denver CN Counter (CNC) [*Wilson et al.*, 1983]. The CNC measures the concentration of particles with diameters from about 0.008 to 2.0 microns. The CNC inlet is alternately heated and unheated to provide nonvolatile and total CN counts, respectively, and has a sampling rate and total accuracy of about 1 Hz and 15%. The cloud was characterized by sudden increases in CN from a typical lower stratospheric value of about 5 $cm^{-3}$ to as high as 1000 $cm^{-3}$. The cloud was structured horizontally and contained both a volatile and a nonvolatile component in a ratio of about 2:1. Figure 1 shows that the cloud was confined in a fairly narrow layer centered on about the 518 K isentropic level. The bottomside of the cloud was sharply defined in the vertical at about 500 K; the plume topside was not penetrated by the ER-2. The ER-2 also encountered a similar, though less dense, cloud on a southbound April 22 flight.

Figure 1

Figure 1

Figure 1 also shows the ER-2 ground track and measured CN concentration reported every 30 seconds. From an initial heading to the north east after leaving the NASA Ames Research Center, the aircraft turned west, and flew from the San Francisco Bay area to a point about 1000 km west of the North American coast at 134° W, then retured to the Bay area. On the initial outbound leg, the CNC instrument detected moderately elevated levels of CN north of the Bay area. On the return leg, the CNC instrument recorded the highest CN levels about 100 km west of the Bay area. During maneuvers prior to landing, the ER-2 passed out of the plume while flying north. The highly structured nature of the cloud makes it difficult to accurately gauge the cloud size and morphology. Still, we estimate that the horizontal dimension of the complete cloud to exceed 100 km. The greatest continuous region where the CN count exceeded 500 $cm^{-3}$ was about 50 km in extent so that we estimate the minimum cloud area as

about 2500 $km^2$. Models of aerosol coagulation, in conjunction with the observed CN concentration, argue that the cloud could not have been more than about 21 days old (**CHUCK, citation here?).

Aerosol particles in the cloud were gathered by the Multi-sample Aerosol Collection System (MACS), a thin-plate inertial impactor that collects particles larger than about 0.02 microns for electron microscopy and individual particle elemental analysis. The elemental analysis revealed that the ratio of the volatile and nonvolatile components was about 3:1, similar to the ratio measured in the CN data. Further, it was determined that the nonvolatile fraction of the aerosol was composed of almost entirely of carbon rich particulate (soot), a rare component of undisturbed lower stratospheric air [*Sheridan et al.* 1994]. The volatile fraction of the cloud aerosol was composed of sulfate droplets. We note that none of the MACS cloud samples showed any evidence of alumina particulate of the type known to be emitted by SRMs.

Nitrous oxide ($N_2O$) concentration in the cloud (when CN exceeded 500 $cm^{-3}$), measured using the ATLAS laser absorption instrument citepodolske, was about 210 -230 ppbv, consistent with $N_2O$ in the surrounding air. $N_2O$ measurements from polar campaigns have demonstrated that very low values of $N_2O$ are associated with the polar winter vortex and its high values of potential vorticity [*Schoeberl et al.* 1992; *Loewenstein et al.* 1990]. The concentration of $N_2O$ at the edge of the polar vortex on April 26, 1997, for example, was less than 100 ppbv. The $N_2O$ observations on April 18, in excess of 200 ppbv, clearly indicates that the cloud can not reasonably be associated with polar vortex air and that the cloud origin must be found in the northern midlatitudes.

We now summarize the main features of the cloud with the objective of establishing its origin. First, CN concentration in the cloud was about 1000 $cm^{-3}$. Second, this aerosol was composed entirely of sulfate and carbon particles in the ratio of about 2:1. Third, the cloud was not more than about 21 days old. Finally, the cloud formed in a

northern midlatitude airmass.

The soot and sulfate composition forces us to conclude that the source was a stratospheric vehicle powered exclusively by hydrocarbon combustion, a high altitude aircraft or rocket. We may reasonably eliminate an aircraft as the cloud source however, by comparison to the measured features of the exhaust plume of the Concorde supersonic transport, the largest known stratospheric aircraft. Fahey et al. [1995] report CN concentration of about 2000 $cm^{-3}$ in the Concorde plume when it was less than 1 km in horizontal extent. CN concentration in the April 18 cloud was only a factor of 2 less less than CN in the Concorde plume, yet the horizontal extent of the cloud was at least a factor 50 greater than the extent of the Concorde plume. Hence, the cloud was too large and too dense to be from a stratospheric aircraft.

By elimination, the cloud source was most likely a large kerosene fueled rocket. A comprehensive search of launch records shows that two rocket launches meet the time and location constraints developed above: (1) launch of a Cosmos satellite from Plesetsk, Russia (65 N, 35 E) on April 9 at 0859UT and (2) launch of the Progress M-34 from the Baikonur Cosmodrome, Tyuratam, Kazakhstan (48 N, 30 E) on April 6 at 1604 UT. The launch vehicle in both cases was the Soyuz booster, a rocket in use for over 40 years.

## Plume Transport Analysis

Having determined that the April 18 plume was produced by one of two rocket launches from central Asia, we apply various meteorological analysis techniques to determine which of the two launches was the most likely source. Note that whether the plume was emitted by the April 6 or the April 9 launch does not greatly affect subsequent analysis with regard to stratospheric impacts since the rocket type was the same for both launches and the plume age at the time of the ER-2 encounter was similar. The analyses adopted, air mass tracing using potential vorticity and trajectory

calculations, illustrate the main features of the plume transport from central Asia to the western North American coast. Niether technique provides unambiguous information on the dynamical history of the airmass sampled over California on April 18.

Trajectory calculations using the GEOS-STRAT analyses were run both forward from the two launch sites and backward from the ER-2 encounter site. These calculations consist of constructing 600 km diameter rings of parcels around the launch or encounter sites and carrying the parcels forward or backward in time, respectively, by the winds from the meteorological analyses. Three trajectory cases are calculated. In the first calculation, a ring of parcels surrounding the Baikonur launch site on April 6 is carried forward for 13 days. In the second, a ring of parcels surrounding the Plesetsk launch site on April 9 is carried forward for 10 days. In the third, a ring of parcels around the site of the plume encounter on April 18 is carried backward for 13 days. Using reasonable estimates of trajectory position errors, altitude registration, and release times, we find that the forward launch site and backward encounter site air parcels do not overlap. The second calculation does clearly show, however, that the launch from Baikonur is the more probable source.

The first trajectory case shows that air from the Baikonur region on April 6 is stretched into two major streamers extending eastward from the launch site in Figure 2 (blue). This figure shows the locations of Baikonur, Plesetsk, and the site of the ER-2 flight on April 18 (stars). The cloud of parcels run forward using GEOS-STRAT data from Baikonur are started on April 6 at 0800 UT as indicated by the 600 km radius black filled circle at 46° N and 63° W. By April 18 that collection of parcels has been stretched and distorted into a mass of air that has drifted eastward towards Japan and a second streamer of air that has come full circle around the globe. Part of this second streamer comes to within about 900 km of the ER-2 intercept site, a large error given the 12-day trajectory.

Figure 2

Figure 2 also shows the second case, a ring of parcels run forward from Plesetsk

on April 9 at 0900 UT (purple). Here, the trajectory clearly shows that air from the Plesetsk region remains confined to the polar vortex and does not reach the plume encounter region. This indicates that the plume was not from the Plesetsk launch; lower stratospheric exhaust from that rocket was trapped in the polar vortex.

The third case, back trajectories from the ER-2 plume encounter (not shown), provides evidence that the plume airmass could have arrived from central Asia following a 10 to 14 day transport, within the 12 day window required for the April 6 launch. These back trajectories also indicate that that some fraction of the encounter airmass was from a region about 1500 km east-northeast of Baikonur, an error that again must be considered large given the 12 day trajectory. Here too, vortex air is excluded from consideration as source airmass.

Trajectories based on alternative meteorological analyses show that these conclusions are fairly robust. Forward and backward trajectories were calculated using the NCEP/NCAR reanalysis, the UKMO data, and the NMC/CPC data. These also fail to show intersection of either Plesetsk or Baikonur air with the ER-2 encounter air. In fact, the trajectories uniformly show the material at even greater separations than the results shown in Figure 2 using the GEOS-STRAT winds. In all cases, however, forward trajectories from Plesetsk remain confined to the polar vortex, well away from the California region.

Ttajectories showing that air over Plesestk was trapped in the polar vortex are consistent with the meteorological analysis of the situation on April 9 leading to the conclusion that the Plesetsk launch took place at the edge of the polar vortex. Reverse domain filling techniques (RDF) have been used to check the potential vorticity values which are used to locate the Plesetsk launch in the vortex (see [*Newman et al.* 1996] for a discussion of such air mass tracing using RDF calculations). These RDF calculations verify that the Plesetsk launch on April 9 took place in the polar vortex edge and that the exhaust from this launch almost certainly became trapped in the vortex as suggested

by the air parcel forward trajectory analyses (Figure 2). These analyses, consistent with the $N_2O$ data showing that the plume did not originate in the vortex, eliminates the Plesetsk launch as the source of the April 18 plume.

Since the air parcel trajectory calculations are not entirely successful relating the Soyux plume to the Baikonur launch site, we wish to test the sensitivity of the air parcel trajectories to (1) release time, (2) diabatic processes, and (3) varying isentropic level. The GEOS-STRAT trajectories show great sensitivity to the initial starting time of the air parcels near Baikonur. This is caused by the evolving synoptic situation near Baikonur during this period. In the GEOS-STRAT analyses, southwesterly flow near Baikonur weakens over the course of April 6. The blue streamer seen in Figure 2 results from this southwesterly flow which carries air northward to the edge of the polar night jet. This air gets caught in the edge of the jet, and moves rapidly eastward. The early starting time for the trajectories leads to the parcels being carried closer to the jet core where they can be more rapidly carried eastward towards California. Air over Baikonur late in the day on April 6 moves directly eastward instead of towards the polar vortex. This sort of trajectory sensitivity to initialization time emphasizes the strict requirements on temporal and spatial resolution in regions with large horizontal wind shears and a rapidly evolving synoptic situation.

The trajectories also show large variations depending on the isentropic surface of initialization. Using a high density cross section of parcels as a function of altitude and latitude, the trajectories show large vertical variation with respect to exact air parcel origin. Trajectories at 435 K came directly from Baikonur according to the trajectory calculation, whereas material 5 K above and below this narrow layer came from no closer than 1000 km to Baikonur on April 6.

We have examined the sensitivity of these trajectories to diabatic heating effects. The results are insensitive to the diabatic trajectories because of the small heating rates at these altitudes during this spring period. In a test set of trajectories initialized

around the encounter site of April 18, we found the potential temperature changes ranged between a 3 K rise and a 5 K descent over a 13 day trajectory run.

The back trajectories from the intercept location on April 18 are insensitive to the starting time of the back trajectories. We have run backward from the actual intercept time of 2300 UT, 1200 UT, and 1200 UT on April 19. The final locations of the back trajectories from these three initialization times were approximately the same. Because of the very weak winds over California over the several days before the encounter, the back trajectory starting time is not a critical parameter.

## Summary and Discussion

The NASA ER-2 intercepted a large, dense aerosol plume on April 18, 1997. Measurement of CN concentration clearly demonstrated the anomalous character of this plume while the sootnd sulfate composition of aerosol impactor samples shows that the plume source was a kerosene based propulsion system. Comparison of the plume size and CN concentration with similar measurements of aircraft exhaust effectively eliminates known aircraft as the source through scale arguments. Analysis of the long-lived constituents in the plume show that it originated at mid-latitudes; the plume could not have come from within the polar vortex. Aerosol coagulation arguments indicate that the plume had been deposited not longer than 21 days prior to the April 18 encounter. Air parcel trajectory analyses allows us to identify the plume source as a Soyuz rocket launched from Baikonur Cosmodrome on April 6, 1997 to resupply the MIR space station. This means that the plume was advected more than 10,000 km over a 12 day period while remaining fairly intact and well defined horizontally and vertically.

The air parcel trajectories provide a poor tracing of the rocket plume both forward from the April 6 Baikonur launch or backward from the ER-2 plume encounter on April 18. Insofar as the plume source was indeed the Soyuz rocket, this illustrates the problem of trajectory error amplification for extended calculations. The plume also serves

as a case study in the limitations of trajectory accuracy under some circumstances. Depending on the isentropic level chosen, material can in fact be directly traced backward to the Baikonur launch site, viz 435 K. Unfortunately, this cannot be done within 10 K of the principal isentropic level where the material was sampled, 516 K. The back trajectories from the ER-2 intercept point are insensitive to release time, while the forward trajectories from Baikonur are very sensitive to wind analysis resolution and release timing.

We acknowledge that we cannot eliminate the possibility that the plume source was a very large kerosene fueled vehicle whose characteristics are not in the public domain. Lower stratospheric flight of such a hypothetical aircraft over central California during mid-April is not inconsistent with the aerosol and $N_2O$ data. The weak winds in the stratosphere over California (as determined from the analyses, ER-2 MMS observations, and radiosonde reports) would allow emitted material to remain relatively undisturbed for some days prior to the intercept. This notion is fraught with difficulties however, such as the required very large fuel consumption (and associated size) of the supposed vehicle and the very rapid plume expansion rates implied by the 100 km extent of the plume. The Soyuz rocket source identification is the simplest explanation of the data.

A more detailed analysis of the plume aerosol data, in conjunction with the $NO_y$ data obtained in the plume, can be expected to lead to increased understanding of the stratospheric chemistry of kerosene fueled rocket motors, especially with regard to environmental impacts (work in progress).

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**Figure 1.** CN concentration as a function of (top left) time and (top right) potential temperature. Observation points are shown in laitude and longitude (bottom left) and potential temperature and latitude (bottom right). CN values greater than $7cm^{-3}$ are shown as the larger filled circle points in the bottom 2 panels.

**Figure 2.** Plots of isentropic trajectory clouds on April 18 at 1200 UT that were released from Baikonur on April 6 (blue), Plesetsk on April 9 (magenta), and the ER-2 rocket plume intercept site on April 18 at 2300 UT. The clouds are initialized on the 516 K isentropic surface over a 600 km radius circle around each site.

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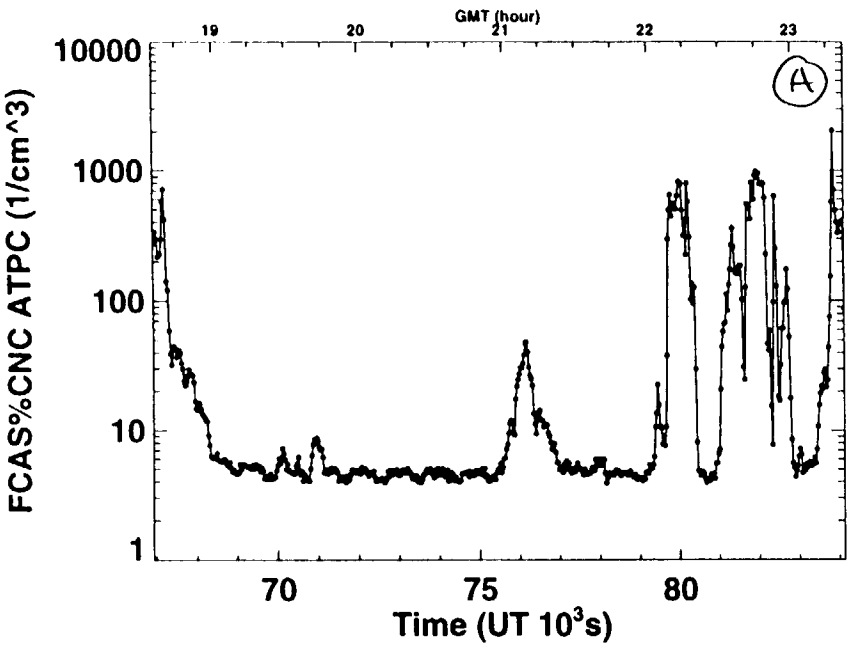
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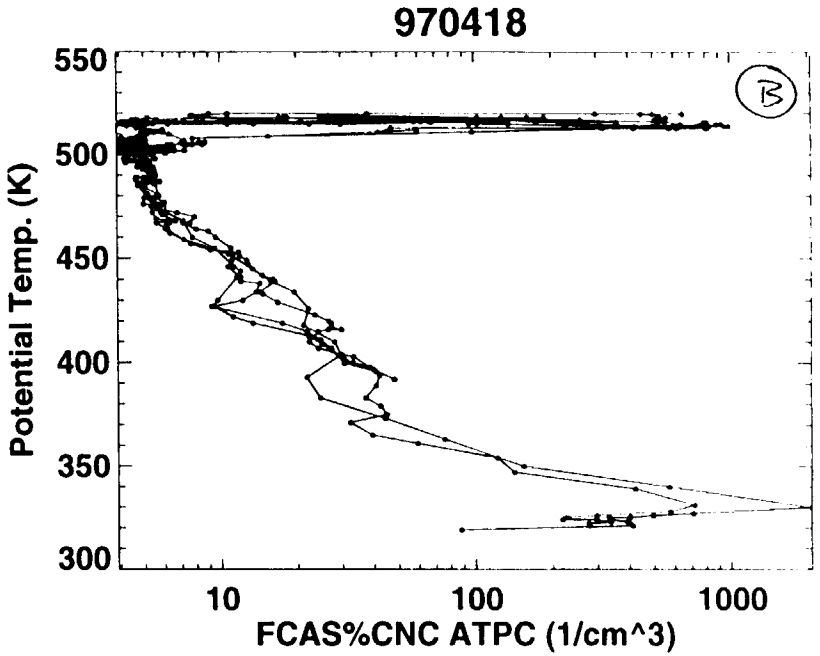
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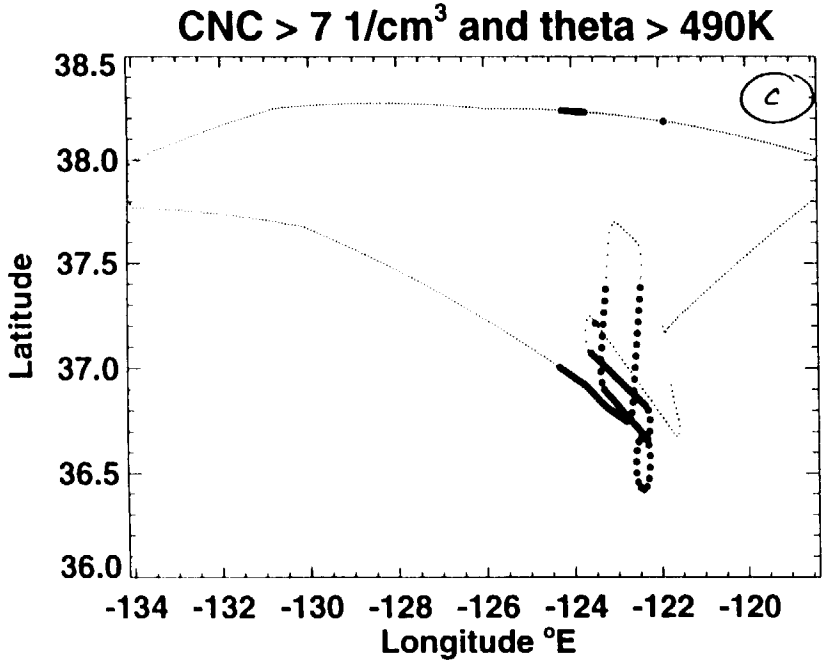
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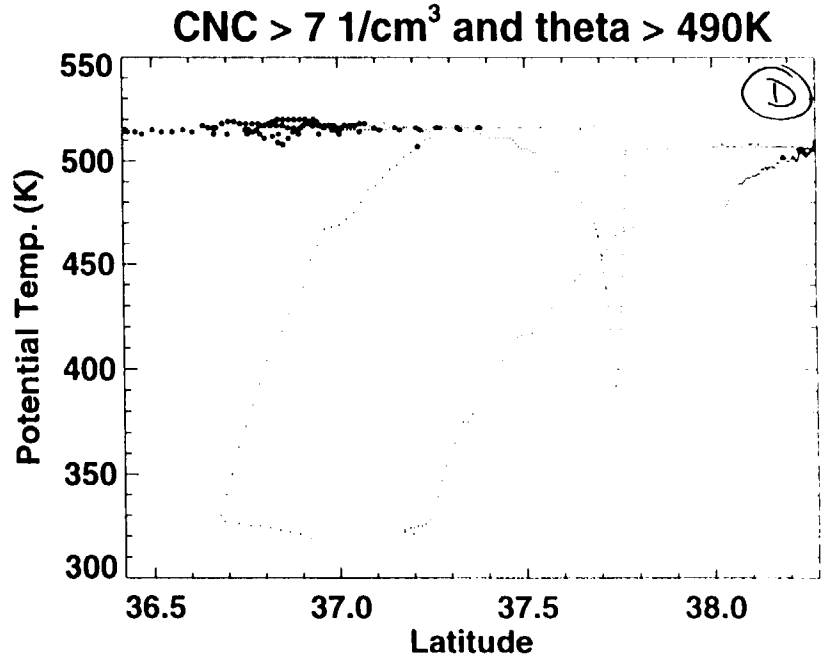
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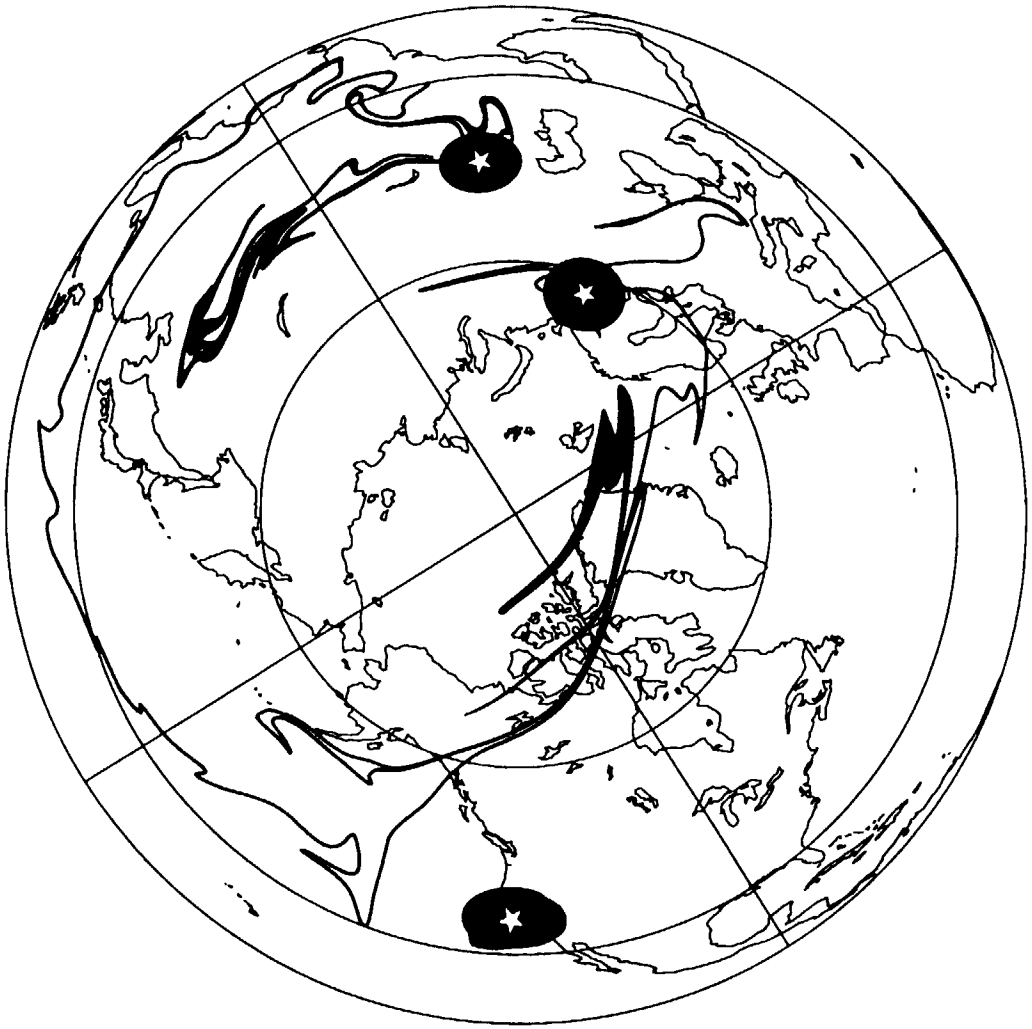

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