Survival of Cirrus Crystals in Clear Air[1]

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ABSTRACT

During the summer of 1966 from Bemidji, Minn., aircraft collections of cirrus crystals were made with a continuous particle replicator. Actual samples show that cirrus crystal trails with a concentrations of 10^5–10^6 m^{-3} can survive a fall of 20,000 ft in clear air with a temperature/dew point spread of 15C. Computations of evaporation rates for falling crystals suggest that it is somewhat surprising that the crystals could have survived under the observed conditions; however, this may have been because input data for the calculations are inadequate.

1. Introduction

Cirrus clouds have long been regarded as forerunners of cyclonic weather disturbances or as passive indicators of specific atmospheric phenomena such as the high-level outflow from tropical hurricanes. Gradually, however, cloud physicists came to suspect that cirrus might play a more active role in the microphysics of lower clouds by serving as a source of ice particles capable of nucleating supercooled clouds in the middle and low levels.

The major unknown in assessing the importance of this latter role has been a lack of knowledge as to the conditions under which a significant number of cirrus crystals could survive an appreciable fall through clear air.

During the 1966 summer operations of The University of Chicago cloud physics group, one of the authors (RRB) observed what appeared to be examples of cirrus seeding of supercooled middle clouds and the subsequent organization of chaotic middle-level convection fields into full-fledged rain storms of considerable size. We immediately organized for a series of flights directed specifically toward detecting and documenting any cirrus crystal remanents that might exist well below the heights of the visible cirrus. This paper reports the results of these flights. Discussion of the role of the cirrus in organizing middle-level convection is the subject of a subsequent report.

2. Technique

Measurements were made from The University of Chicago cloud physics airplane. This plane, a Beech D-18, is equipped to measure several cloud and clear air parameters. For the present study, the most important item of instrumentation was the continuous cloud particle replicator described by Spyers-Duran and Braham (1967). This device operates on the principle of encapsulating cloud and precipitation particles in a continuously moving ribbon of Formvar plastic. It is similar in principle, though not in detail, to the device previously described by MacCready and Todd (1964).

On several days of visible cirrus development, the replicator was operated in clear air at flight level temperatures between about −5 and −15C for the express purpose of collecting any cirrus particles that might have been present. After returning to the ground, the replicator tapes were examined for size, shape and concentration of any crystals collected.

Cirrus crystal collections were made on 7 days which divide into 2 groups depending upon the types and levels of clouds present: a) 3 flights were made on days when there were no visible clouds between the collection level and the cirrus level; and b) 4 flights were made on days when other clouds were present at or near flight level, but where the data suggest that the crystals had their origin in the cirrus. Obviously the first group is most useful for providing information about the survival of cirrus crystals in clear air.

Photographs of the cirrus were made from the airplane and from the ground. In addition to a 16-mm time-lapse camera on the ground, on 4 days we had the use of the stereophotogrammetry set-up used by Harrington (1967) for accurate triangulation of cloud positions and heights. For these days cirrus heights are known within rather small limits, for the other 3 days cirrus heights have been computed from the time-lapse movies and are known less accurately.

Data on the temperature, moisture and wind structure of the atmosphere were determined from the standard radiosonde observations from International Falls, Minn., (INL) and Bismarck, N. Dak. (BIS), respectively, about 90 mi northeast and 290 mi west

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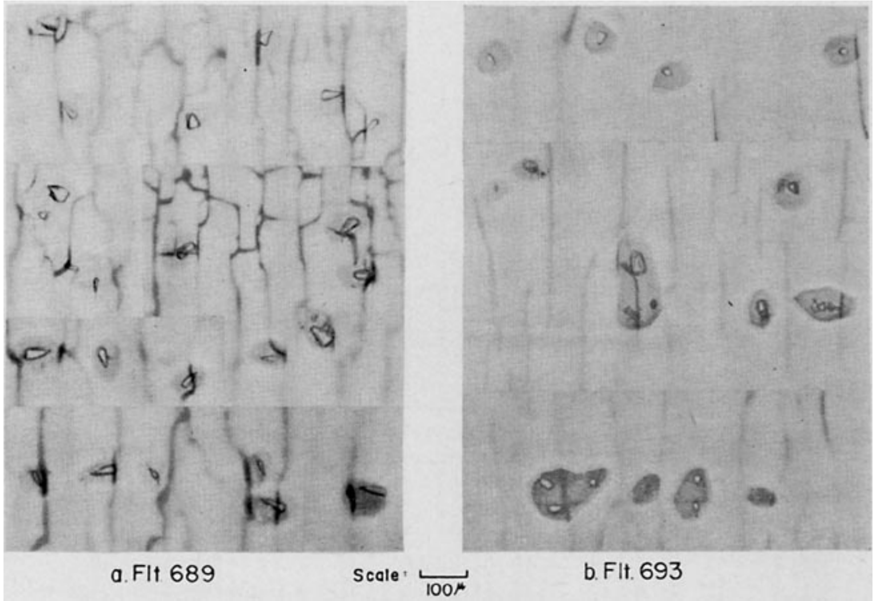

Fig. 1. Photographs of cirrus crystals collected on a., Flight 689, 8 July 1967, and b., Flight 693, 20 July 1967.

of Bemidji, Minn. These data were supplemented with measurements from the airplane up to and including the levels of crystal collections.

3. Results and examples of the data

On every flight beneath visual cirrus we collected ice particles at one or more points in the clear air. Examples of these are shown in Figs. 1a and 1b. These photographs were printed directly from the Formvar ribbon and its transparent polyester backing tape. Shown are some of the largest and best defined of the crystals obtained. Note that they are essentially

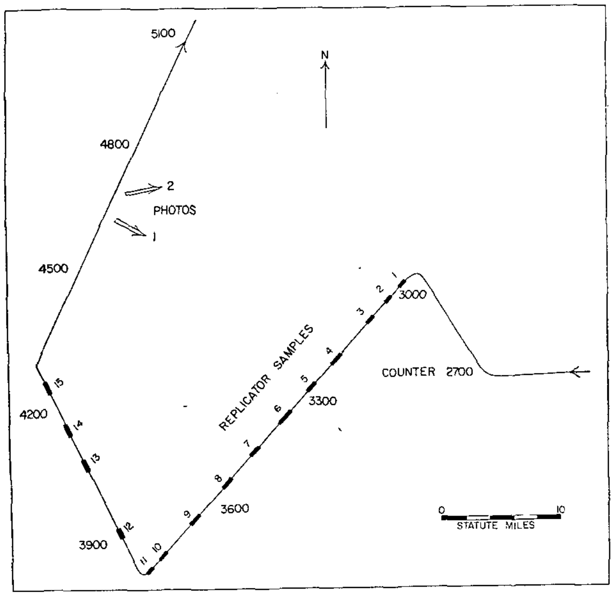

Fig. 2. Portion of flight path, Flight 689, along which crystals were collected.

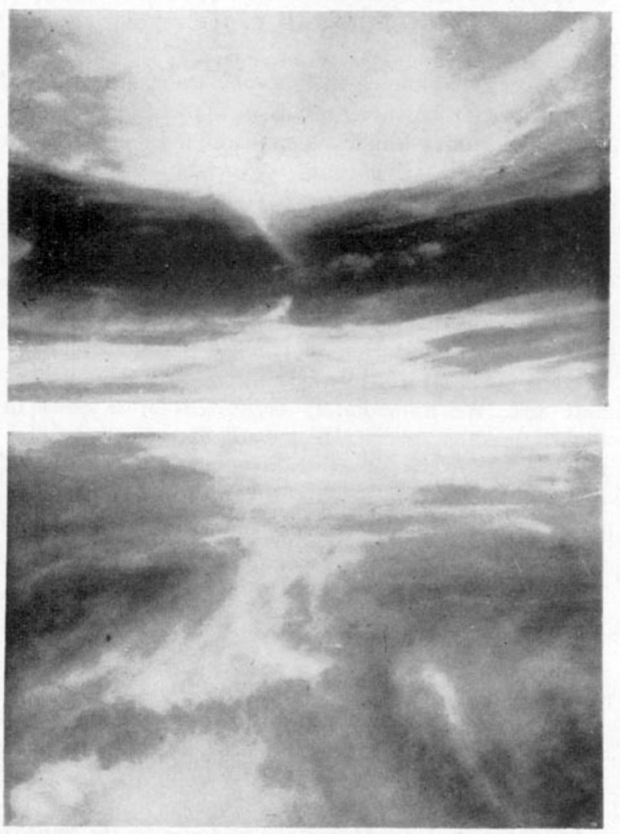

Fig. 3. Photographs of cirrus above flight level, Flight 689.

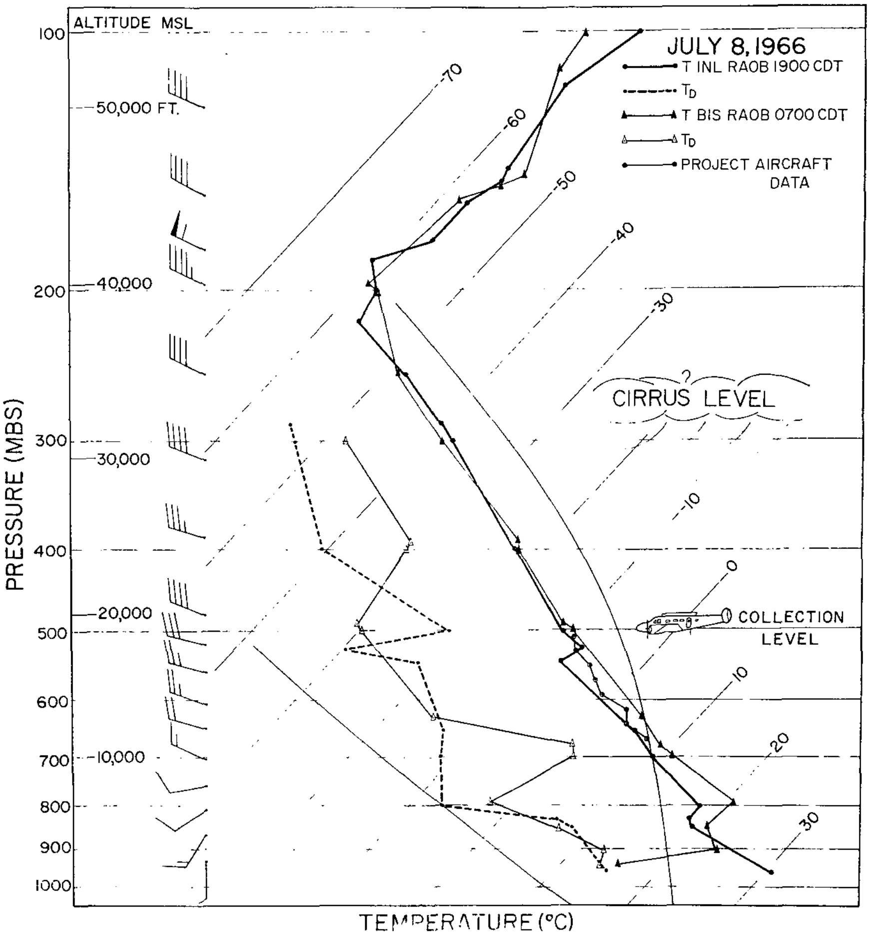

FIG. 4. Temperature, dew point and wind sounding near time of Flight 689.

void of surface features as a result of their erosion, or evaporation, in the dry air. These crystals range in length up to about 70 μ. The smallest crystals that can be identified with confidence are about 10 μ in length. Most of the crystals replicated were less than about 40 μ in length.

The shadowy pattern of lines in the background is due to cracks which developed in the Formvar as it was rolled up after exposure. These are at various depths in the film; hence, most of them are slightly out of focus on the print. An effort has been made to reduce the intensity of these cracks by dodging the background areas. This accounts for the darker areas immediately surrounding the crystals.

These crystals have been identified as having originated in the cirrus by several factors:

1) Complete absence of visible cloud between the collection level and the cirrus level on the 3 best flights.
2) Presence of pyramid or bullet-shaped crystals and pointed columns, which are known to characterize cirrus but which are unreported from other cloud types. In fact, laboratory studies by Kobayashi (1965) showed that pyramid faces were limited to crystals growing at temperatures below -50 ± 5C.
3) Presence of numerous hollow ended columns. These are very commom cirrus crystals. However, laboratory data suggest that they can grow over wide ranges of temperatures colder than -6C, provided that the vapor concentration is about 0.08 gm m^{-3}. This would be above ice saturation, but substantially below water saturation in the temperature range -6C to about -30C. [See Kobayashi (1958).]

Concentrations of these particles were found to range up to more than 10^6 m^{-3} on some of the flights. For the purpose of computing concentrations we have assumed a hydrodynamical collection efficiency of unity, i.e., we assume that all particles from the swept volume of the collector slit are actually replicated. The collection efficiency of the replicator for these small particles is unknown. Calculations following Langmuir and Blodgett (1946) suggest collection efficiencies of 25–50%, much less than unity. However, we believe that it is

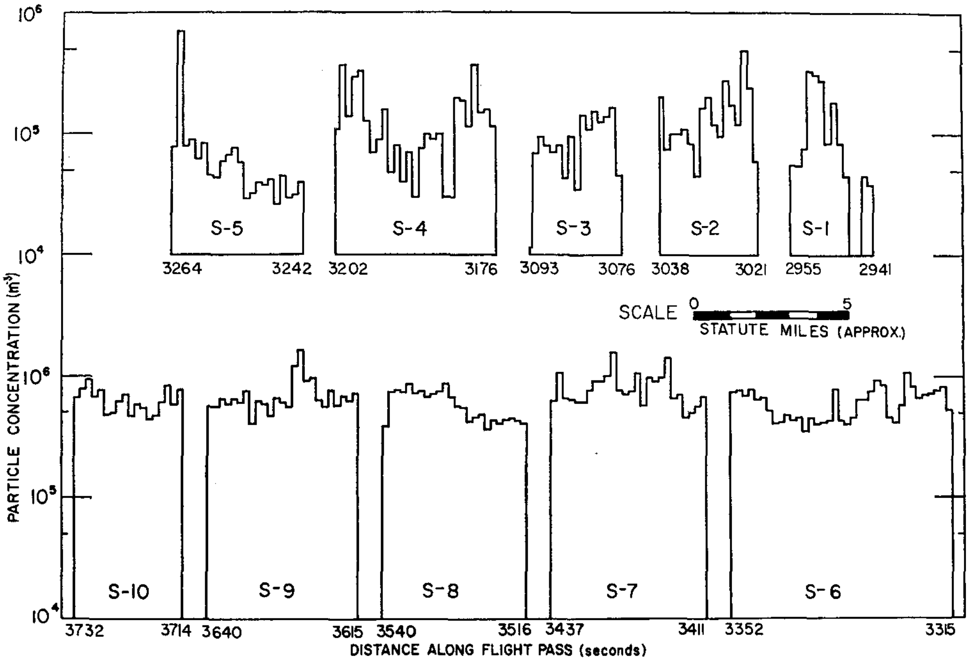

FIG. 5. Crystal concentrations during portion of Flight 689.

higher than this, perhaps greater than unity, because of air flow disturbances created by the sampling slit. At this time it is not deemed worth a serious effort to calculate a more exact value since, in any event, the concentrations are sufficiently high to suggest the importance of cirrus crystals in cloud nucleation.

Flight 689, 8 July 1966. This flight provides some of our best data (Fig. 1a). The replicator was operated at 18,000 ft for a series of short intervals distributed along the flight path as shown in Fig. 2. Also indicated are flight counter times in elapsed seconds and the positions and directions of two cirrus photographs shown as Fig. 3. These two pictures are selected from about 50 taken during Flight 689. The temperature and moisture structure of the atmosphere about the time of this flight is plotted in Fig. 4. On this day there was a broken layer of cirrus uncinus, spissatus and fibratus. Their heights were computed to be about 32,000 ft based upon known winds and the calculated speed and direction of their motion as recorded in ground based time-lapse photographs. The average temperature/dew point spread between 18,000 and 32,000 ft was about 14C. This corresponds to an average relative humidity of about 27%.

Fig. 5 shows concentrations of ice particles as a function of time (seconds) along the flight path for the first 10 sampling intervals. Note that the distances between sampling intervals are not shown to scale. We see that the crystal concentrations increased fairly steadily from about 10^5 m^{-3} in sample 1 to about 10^6 m^{-3} in sample 10 over a distance of about 35 mi. The variations within samples is probably due in part to sampling variability and in part to real variations in crystal concentrations.

Flight 693, 20 July 1966. On this day the airplane flew at 16,400 ft (−4C), and we found crystals from cirrus located between 35,000 and 44,000 ft. The cirrus heights were determined on the basis of 14 data points, corresponding to cirrus tops and heads of cirrus trails, evaluated from the stereophotographs. Examples of crystals collected on this flight are shown in Fig. 1b. Typical concentrations on this flight are order 10^3 m^{-3}. Radiosonde observations (Fig. 6) show that the mean temperature/dew point spread between the cirrus level and the collection level was about 15C, the average relative humidity being about 26%. Fig. 7 shows two views of cirrus clouds occurring during the flight.

Flight 704, 6 August 1966. This flight is included as an example of the second of the two types of flights. For this date, clouds were reported by the flight scientist as scattered to broken cumuli mediocris (bases 3,800, tops 10,000 ft MSL); scattered cumulus congestus (3,800–17,000); a few isolated cumulonimbus (3,800–25,000 estimation); and cirrus fibratus and cirrus spissatus. The stero-camera data give points on the cirrus tops ranging between 29,000 and 33,000 ft, with a modal value of 30,000 ft. The crystal collections were made at 14,5000 (−4C) making passes through several of the cumulus congestus. The replicator was operated for long intervals between clouds as well as through them. A schematic representation of part of this flight is shown in Fig. 8. The replicator was run for the interval indicated by the double bar. Cloud C was a cumulonim-

TABLE 1. Summary of cirrus crystal collections.

Date (1966) Flight no.	22 June 681	8 July 689	20 July 693	25 July 697	6 August 704	9 August 705	16 August 708
Cloud conditions	Cu fra. As, brkn to ovc (7–14) Cs	Ci unc. Ci fib. Ci spi.	Ci unc. Ci spi. Ci fib.	Cu fra. (2–3.5) Ac As (9–10) Ac cas. (9–20) sctd Cu cong. (−25) Ci fib. Cb (distant)	Cu med. (3.8–10) sctd Cu cong. (3.8–17) few Cb (3.8–25) Ci fib., spi.	Brkn Sc (4.6–11) with ocnl Sc dome to 12.5K Ci fib.	Sctd Cu hum. (4.6–7.5) Cu med. (4.6–10) isolated Cu cong. (4.6–12) As (20–21 est.) with virga Ci spi.
Cirrus level							
median	20K	32K		?			
range			35–44K		29–33K	27–33K	27–40E
median temp	−10C	−46C	−50C	?	−46C	−45C	−46C
Avg. temp./dew point spread	16C	14C	15C	12C	13C	10C	12C
Collection							
height	18.8K	18K	16.4K	19K	14.5K	11.2K	17K
temp.	−9.6C	−9.2C	−4C	−10C	−4.2C	−5C	−10C
Location of cirrus collections	clear air	clear air	clear air	clear air between AC cas.	edges of Cu cong. clear air between Cu cong. tops	Sc domes and clear air nearby	clear air below As lyr
Typical max. conc., (m^{-3})	10^5	10^6	10^5	10^6	10^3	10^4	10^6

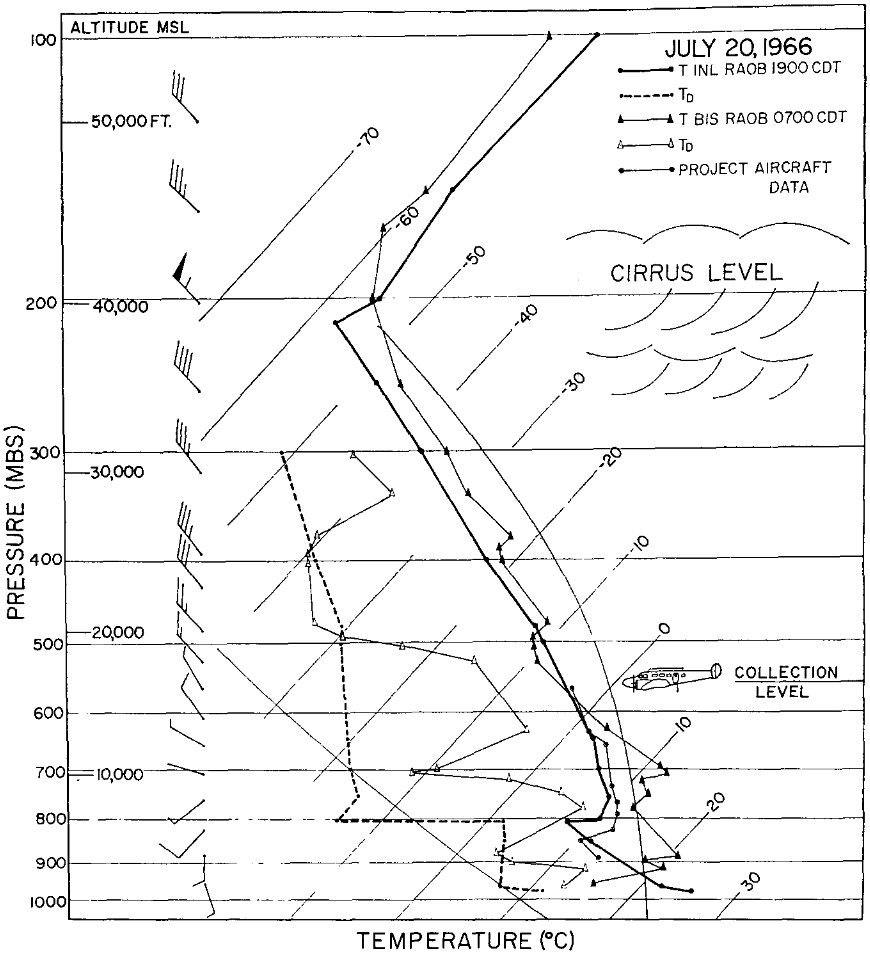

FIG. 6. Temperature, dew point and wind sounding near time of Flight 693.

Fig. 7. Photographs of cirrus above flight level, Flight 693.

bus with a top estimated over 25,000 ft. It contained cloud drops with admixed prism crystals up to about 600 μ length in the interior parts and large snow crystal clusters at its edge. Cloud D had a flight level diameter of 0.4 mi and a top of 17,000 ft as computed from flight camera data. It was found to contain an all-liquid core and a mixture of drops and crystals at the edges. These crystals were both 60 μ bullets and irregular crystals up to 300 μ in length. Cloud E had a flight level diameter of 1.5 mi and a top of 17,800 ft, and contained a heavy concentration of liquid water mixed with snow pellets of low concentration.

For our present purpose the important part of this flight is the 6-mi clear air path between cloud D and cloud E. This region was found to be entirely smooth and free of high-frequency indicated, airspeed fluctuations which we associate with cloudy air or air that recently has been in cloud. On this basis we conclude that this air had not been in cloud for some considerable time, perhaps 30 min or more. Throughout this entire region between cloud D and cloud E we replicated a low concentration of bullet crystals which we attribute to the overlying cirrus.

A summary of the observations from all 7 flights is given in Table 1. In this table the cloud conditions are abbreviated in accordance with the *International Cloud Atlas* (World Meteorological Organization, 1956); base and top heights (in parentheses) are given in thousands of feet; cirrus heights were triangulated from ground photographs; and temperature and dew-point depressions are taken from the close available raob data.

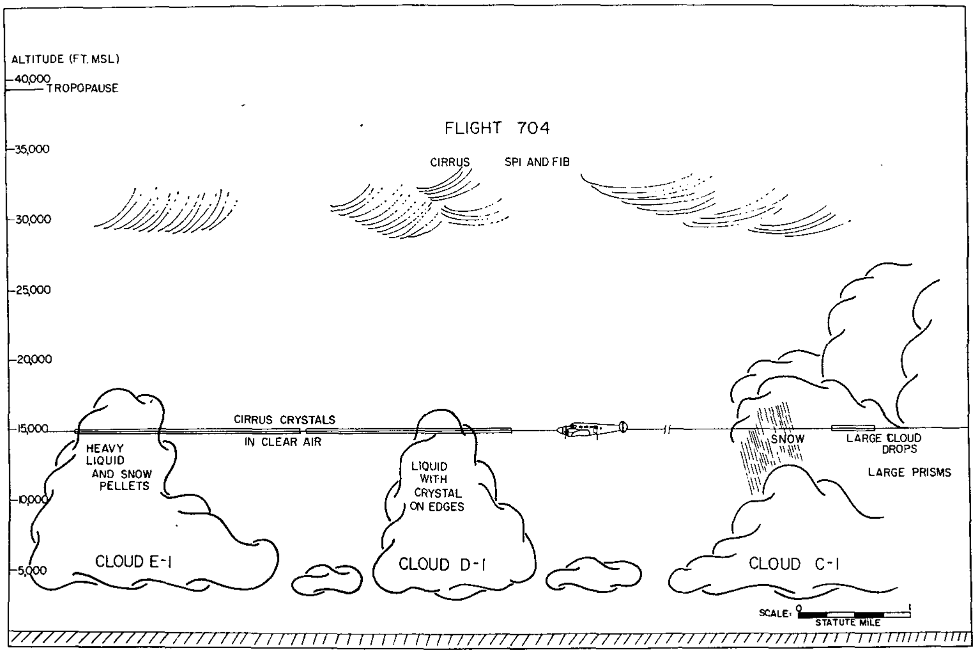

Fig. 8. Schematic view of portion of Flight 704, showing conditions associated with clear air collections.

Note that Flights 681, 689 and 693 give the best information about cirrus crystal survival.

4. Discussion

Data from these flights show that cirrus crystals can survive a fall through relatively dry air for distances, and in concentrations, that we had not anticipated when we began the flights. It was natural then to ask whether we understand *how* these crystals could survive in such numbers. Thus, a study was undertaken to compute the rate of evaporation of cirrus crystals falling under the conditions of Flight 689. Such a calculation involves two interdependent steps. We must compute a) falling speeds for crystals of proper shapes and sizes, and b) evaporation rates, i.e., heat and mass exchange rates between the crystals and their environment. In the Stokes region, where the crystals are small, the problem is somewhat easier since we can calculate both falling speeds and evaporation rates from first principles. In our problem the Stokes region is limited to a few meters near the collection level. Therefore, for the bulk of the problem, we must turn to engineering studies for values of drag coefficients C_d and heat exchange coefficients (Nusselt numbers, Nu) as a basis for estimating falling speeds and mass exchange rates.

We have not found these engineering data for proper shapes of particles over the required range in Reynolds numbers. Therefore, we have carried out two sets of computations. The first was for evaporating spheres, which do not resemble cirrus particles, but for which drag coefficients and heat exchange data are reasonably accurate. The second calculation was for short columnar crystals, of a size and shape similar to that of the collected particles, but for which we had to use approximate engineering data taken under conditions not strictly applicable to our problem.

For the sphere calculations we used the classical equation for growth of a stationary sphere multiplied by a ventilation coefficient F (Frössling, 1938) to give particle radius r as a function of time t, i.e.,

$$r^2 = r_0^2 + \frac{2m_w D(\Delta e)}{\rho_i RT} Ft, \tag{1}$$

where

$$F = 1 + 0.229(\mathrm{Re})^{0.5},$$

and where D is the diffusivity of water vapor in air, ρ_i the density of ice, m_w the molecular weight of water vapor, R the gas constant, and T the temperature. The term Δe is the vapor pressure difference between the particle and its environment; thus, allowance had to be made for the reduction in particle surface temperature due to evaporation, i.e.,

$$\Delta T = \frac{L_s D m_w}{kRT} \Delta e, \tag{2}$$

where k is the thermal conductivity of air and L_s is the latent heat of sublimation of ice.

In the Stokes region the fall speeds for spheres can be specified directly. This can then be combined with the evaporation equation, applied in reverse to obtain the heights above the collection level where particles would have had a particular size. Thus,

$$\delta z = V\delta t = \frac{2}{9} \frac{g\rho_i}{\mu} r^2 \delta t,$$

where μ is the viscosity of air and g gravity.

Beyond the Stokes region, falling speeds for the spheres were computed after the manner of MacDonald (1960). Because Δe, T, L_s, D, k and μ are functions of altitude, while F and V, the falling speed, are functions of both altitude and particle size, and because the evaporation rate and fall distance equations are interdependent, they must be solved simultaneously using very small time steps.

Calculations for the short columns also were carried out in two parts. In the Stokes region we made use of the classical relationship involving the "electrostatic capacitance" factor for which we computed values following MacDonald (1963). Taking the crystal as a short segment of a circular cylinder with length l twice its diameter we have

$$\frac{dM}{dt} = \frac{3\pi\rho_i}{16} l^2 \frac{dl}{dt} = \frac{4\pi CDm_w}{RT} (\Delta e). \tag{3}$$

From MacDonald (1963) we have $C = 0.33l$, therefore,

$$l^2 = l_0^2 + 14.08 \frac{Dm_w(\Delta e)}{\rho_i RT} t. \tag{4}$$

Falling speeds for the short columns, in the Stokes region, can be computed directly. Thus, the fall distance equation becomes

$$\delta z = V\delta t = \frac{\pi}{96} \frac{\rho_i g}{\mu} l^2 \delta t.$$

For particles beyond the Stokes region, evaporation rate computations make use of heat exchange data as expressed in Nusselt numbers. Thus,

$$\mathrm{Nu}_l \equiv \frac{hl}{k} = \frac{(dQ/dt)l}{Ak\Delta T}, \tag{5}$$

where h is the heat transfer coefficient, A the surface area of the particle and ΔT the temperature difference between the crystal and its environment. From this we have

$$\frac{dQ}{dt} = L_s \frac{dM}{dt} = \frac{\mathrm{Nu}_l A k \Delta T}{l}. \tag{6}$$

We were not able to find Nusselt number data exactly suited to the problem. Pasternak and Gauvin (1961) give $Nu_l = 0.635(Re'')^{0.5}$ for irregular particles where Re″ is a Reynolds number based upon a "characteristic" dimension. Eckert and Dale (1959) give $Nu_l = 0.52(Re)^{0.5}$ for cones in turbulent flow. We have chosen

$$Nu_l = 0.55(Re)^{0.5}$$

as a compromise between these two expressions. At Reynolds numbers corresponding to sizes less than 100 μ the Nusselt number (on length) was taken as equal to 2.6 in view of its interpretation as the ratio of convective heat loss to conduction heat loss. [The value 2.6 comes from equating (3) and (6) and substituting from (2)]. By substituting for dM/dt, from (3) into (6), we obtain

$$l^2 = l_0^2 + \frac{16}{3}\frac{k\Delta T Nu_l}{L_s\rho_i}t. \qquad (7)$$

To obtain falling speeds for short columns beyond the Stokes region we again apply the method of MacDonald. Drag coefficient data for an infinite cylinder in normal flow, over a wide range of Reynolds numbers, is given by Hoerner (1958). To these we applied a scaling factor, 0.54, which is the ratio of drag of a circular cylinder segment (with length-diameter ratio of 2) to the drag of an infinite cylinder at a Reynolds number of 10^5 (Prandtl and Tietjens, 1934). Changes in this scaling factor as we go from columns with a length/diameter ratio of 1 to a ratio of 5 appear trivial compared with other uncertainties. It would make the calculations firmer, however, if we had C_d data for short cylinder segments over a wide range of Reynolds numbers.

As in the case of computations for the sphere, the interdependence of the evaporation rate and falling speed equations, and the variation with altitude of most of the parameters, required solving the two equations simultaneously using small time steps.

Computations were made for two different assumptions about the moisture conditions in the levels where the crystals are evaporating. Condition I uses the average dew-point data from Fight 689. Condition II assumes just one-half the moisture deficit indicated by Condition I. The results of these calculations are shown in Table 2, where for ease of understanding we have turned the problem around and show the sizes that the particles would have had to have been at various heights in order to reach the collection level with a diameter (spheres) or a length (prisms) of 20 μ.

We note from Table 2 that most of the mass loss and size change occurs in the last 5000 ft of a particle's fall. This results from two factors. The first is simply that their greater sizes, and thus higher fall speeds at the upper levels means that crystals spend less time at the upper levels. The second and more important consideration is that the rate of mass loss is directly proportional to the difference in vapor concentration between a crystal and in its environment. Because of the very low temperatures at cirrus levels, the total capacity of space for water vapor is small with the result that the actual rate of mass transfer (not the relative rate) is fairly insensitive to the relative humidity. To illustrate this point, recall that the saturation vapor density at −40C (300 mb) is 0.1194 gm m^{-3} and at −10C (500 mb) is 2.1548; thus, a 50% saturation at the upper level would give a vapor density difference equivalent to 97% saturation at the lower. The survival of cirrus crystals is much more sensitive to the humidity at −10C and −20C levels than it is to the humidity at the cirrus levels.

TABLE 2. Computed sizes for ice spheres and prisms which could survive a fall to 20,000 ft with a size of 20 μ under two moisture conditions.

Moisture condition	Spheres Diameter (μ) I	II	2×1 prisms Length (μ) I	II
Altitude (ft)				
30,000	870	650	860	640
25,000	785	590	780	580
20,000	530	400	515	400
19,000	400	310	425	335
18,000	20	20	20	20

The actual sizes computed for both the spheres and the 2×1 prisms are too large to be compatible with cirrus observations. Recall that Weickmann (1947) shows many examples of cirrus prisms about 500 μ in length.

Therefore, we must conclude that it is somewhat surprising that these crystals could have survived a fall under the conditions of Flight 689. We hasten to point out, however, that in addition to the inadequate engineering data used in the calculations, there are several additional factors which were ignored completely. First, these calculations assume that the temperature difference between the crystals and their environment is determined by the entwined heat and mass exchange processes. Cloud physicists customarily make this assumption, but in the case of crystals in a dry upper atmosphere an additional heat loss by radiation could be of significance. Dessens (1966) and Gotaas and Benson (1965) have reported evidence of the importance of this form of heat exchange in cloud physics problems. The second factor is that the temperature-moisture values reported by the radiosondes may not accurately reflect the conditions directly along the paths of the falling crystals. More than likely, this region would be colder and more moist than seen by the raobs. The third factor is that we have used still air terminal speeds for single particles as the rate of descent for these clouds of particles. This can be in error in two ways, i.e., there could be a gentle downward drift to the air in the cirrus trails and there could be some increase in fall speed due to interaction with adjacent particles (this however is thought to be small). All three of these factors work toward making crystal survival more likely.

The 10^6 concentrations observed in the collections should not be taken to imply such concentrations in the cirrus of particles of the size computed in Table 2. The computations did not take into account the distribution of sizes in the collections and, equally important, there must be a convergence of the crystals as they slow up with evaporation. Ultimately, of course, this is offset by the complete evaporation of the smaller ones.

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