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A New Scenario for the Formation of Striations in the Dust Tail of Comet Hale-Bopp (C/1995 O1)

ZDENEK SEKANINA
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, U.S.A.*

HERMANN BOEHNHARDT
European Southern Observatory, Santiago, Chile

OLIVER RYAN
Department of Physics, National University of Ireland Galway, Galway, Ireland

KURT BIRKLE
Max-Planck-Institut für Astronomie, Heidelberg, Germany

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PROJECT STATUS AND RATIONALE FOR A NEW SCENARIO

- For the first time, motions of striae across a comet's dust tail (Fig. 1) were recently satisfied over periods of up to 16 days (Fig. 2) by three-parameter formalism of two-step dust fragmentation model, which was introduced in 1980 by Z. Sekanina & J. A. Farrell (Astron. J. 85, 1538–1554)

- This model is based on premise that following its release from comet nucleus, parent mass suddenly disintegrates into cloud of microscopic, predominantly submicron-sized, grains that are subsequently swept antisunward by solar radiation pressure to form striation across dust tail

- Three parameters of this model include: time of release of parent mass from nucleus, solar repulsive acceleration (radiation pressure) that this mass is subjected to, and time of its fragmentation; additional constraint is provided by range of radiation pressure accelerations on particle fragments in stria

- Constraints set by available data on striae indicate dichotomy, model's major weakness: parent masses must be meters to tens of meters across to account for observed stria prominence, yet they are found to be subjected to high repulsive accelerations typical for micron- and submicron-sized dust grains

- Critical point: Are these high accelerations indispensable for understanding of formation and evolution of striated tails? Search for answer to this question in case of Hale-Bopp is subject of our investigation

INTRODUCTION OF A SIX-PARAMETER FORMALISM

- Existing dust fragmentation model is generalized by assuming that a parent mass separates from the nucleus (or leaves its gravitational field) with a finite (rather than zero) release velocity, thereby expanding from three to six the number of this model's parameters
- Computer algorithm allows user to search for release velocity components in RTN coordinate system (whose axes are oriented in radial, transverse, and normal directions at point of release, referred to comet orbit plane) or in standard ecliptical system
- Built-in options of our iterative least-squares differential-correction technique allow user to solve for all, or any combination of fewer than, six parameters of this model
- Addressing issue of model's weakness, we focus on solutions with no repulsive acceleration on parent mass (i.e., assuming purely gravitational motion)
- Extensive experimentation with our optimization technique has never resulted in successfully converging five-parameter solution, indicating time of parent release to remain indeterminate; this has left search for set of release time dependent four-parameter solutions coupled with their critical assessment as our most hopeful *modus operandi*
- To investigate feasibility of this approach, we conduct three major tests

RESULTS OF TEST RUNS

- Test 1 is an effort to satisfy 271 points measured for most prominent striation on 13 images of Hale-Bopp's dust tail taken between March 2 and 15, 1997, which were fitted successfully by three-parameter formalism:
  - Retaining values for times of parent release and fragmentation, 57.48 and 38.51 days before perihelion, respectively, as obtained from three-parameter formalism, and forcing parent repulsive acceleration to be zero instead of 0.572 Sun's attraction, we find that a satisfactory solution (mean residual of ± 0.0136 million km) requires unacceptably high parent-release velocity of 3.10 ± 0.14 km/s, nearly in antisunward direction
  - Retaining value for time of fragmentation, forcing repulsive acceleration to be zero again, and solving for time of release along with release velocity components fails to yield any converging solution
  - Retaining value for fragmentation time, forcing zero repulsive acceleration, but allowing release time to change stepwise from run to run, beginning at 70 days before perihelion and proceeding back in time, we obtain a set of solutions that satisfy 208 to 266 of 271 points and show strong dependence of release velocity on release time (Fig. 3)
  - Since parent objects are massive bodies, their release velocities should be much lower than peak ejection velocities for microscopic dust grains; this excludes parent release at heliocentric distances smaller than ~100–150 AU

RESULTS OF TEST RUNS (CONTINUED)

- In addition, parent release at times from ~80 to ~300 days preperihelion (heliocentric distances ~1.6 to ~4 AU) is also ruled out by an unsatisfactory representation of significant fraction of measured points
- On the other hand, solutions rapidly deteriorate, with their convergence increasingly more difficult, for wide range of preaphelion release times
- We find that most satisfactory solutions refer to release points between aphelion and ~200 AU postaphelion and to release velocities near 3–5 m/s, nearly in forward direction; this signals need for next phase of test runs

- Test 2 is a search for sets of best four-parameter near-aphelion solutions for six selected striae, based on all data points available; the aim is to compare preaphelion, aphelion, and postaphelion solutions for each stria in terms of release velocity (both its magnitude and direction), total number of points satisfied, and mean residual involved:
    - With only minor differences, our analysis of six cases leads to results that can largely be described in common terms
    - Minimum release velocity, ranging from 2.2 to 5.4 m/s, is attained when parent release occurs not too far from aphelion; choice of release time has no dramatic effect on number of points satisfied and on mean residual (Fig. 4)

RESULTS OF TEST RUNS (CONTINUED)

  - For given parent-release time, release velocity vectors are distributed, with high accuracy, along great circle, covering arc of 110° to 130° long (Fig. 5)
  - Calculated polar locations of these great circles vary systematically from R.A. = 294°, Decl. = −72° for parent release ∼0.4 orbital period prior to aphelion (at ∼200 AU from Sun) to R.A. = 287°, Decl. = −55° for release ∼0.4 orbital period after aphelion
  - Normal component of release velocity correlates with its vector direction, depending on release time for given stria and on stria for given release time
  - To verify that these six striae are not exceptional in terms of orientation of their release velocity vectors, further testing is warranted

- Test 3 is restricted to parent release at aphelion, but it extends our search for best four-parameter solutions to total of 35 striae, in order to gather more information on distribution of parent-release velocity vectors
  - Extended set of striae shows that parent-release velocities at aphelion range from 1.5 to 5.4 m/s, closely confirming results from small set
  - Extended set also confirms strong concentration of release velocity vectors to great circle, along arc not exceeding ∼130° in length and its pole located at R.A. = 290°.1, Decl. = −65°.5

CONCLUSIONS

- We find no need for high (indeed, for any) repulsive accelerations acting on massive parent bodies ($\sim 10^9$ to $\sim 10^{12}$ g) whose sudden fragmentation into microscopic dust triggers formation of striations in dust tail of Hale-Bopp

- However, any dynamically plausible scenario compliant with purely (or almost purely) gravitational orbits of parent masses requires that these objects be released from nucleus (or its gravitational grip) with low velocities ($\ll 10$ m/s) at very large heliocentric distances, along aphelion arc of Hale-Bopp's orbit

- Because of lack of activity, parent-mass release at ≥ 200 AU from Sun cannot be outgassing-triggered ejection; we suggest two possibilities:
  - Spontaneous, activity independent, *in situ* (i.e., far from Sun) separation from nucleus, apparently rotation assisted
  - Release from comet-bound trajectories, making these objects temporary satellites of main nucleus; in this case, there are two possible subscenarios:
    - Outgassing-triggered, low-velocity (and rotation assisted) ejection into temporary comet-bound orbit near perihelion at previous return to Sun
    - Common origin with, or as consequence of tidally-triggered formation of, major satellite (Sekanina 1999, Earth Moon Plan. 77, 155–163) at time of Hale-Bopp's presumed close encounter with Jupiter (Marsden 1999, Earth Moon Plan. 79, 3–15) along inbound orbit at previous return

CONCLUSIONS (CONTINUED)

- Nuclear rotation is bound to have played major role in process of releasing parent masses, as apparent from two lines of evidence:
  - First and foremost, vectorial distribution of parent-release velocities along great circle is undeniably effect of conserved angular momentum of nucleus at time of release; derived coordinates of rotation pole are in good agreement with independent determinations, even though these refer to other times (also, cf. Sekanina et al. 1998, Planet. Space Sci. 46, 21–45 for very similar effect detected in vectorial distribution of separation velocities of nuclear fragments of D/1993 F2, Shoemaker-Levy 9)
  - Second, release velocities of parent masses are comparable in magnitude with, or are lower than, Hale-Bopp's equatorial rotational speed of 5.4 m/s
- Temporary-satellite scenarios for parent masses are attractive because release velocities appear to be constrained by escape velocity from nuclear surface at one end and escape velocity from comet's gravity well at other end
- Fragmentation of parent masses apparently occurred on time scale of fraction of one day; Sekanina & Pittichová's (1999, Earth Moon Plan. 78, 339–346) constraint of <2–3 days represents crude upper limit, as it does not consider smearing due to sidereal tracking, possible effects of striation duplicity, etc. (cf. Ryan et al. 1999, JPL Cometary Science Team Preprint No. 183)

CONCLUSIONS (CONTINUED)

- Fragmentation/disintegration events of very short duration could be similar in nature to flare-ups that according to Sekanina & Boehnhardt (1999, Earth Moon Plan. 78, 313–319) contributed to Hale-Bopp's 1996 porcupine-like coma morphology, and to sudden dust bursts detected in KOSI-9 laboratory simulation experiments (Grün et al. 1993, J. Geophys. Res. 98, 15091–15104)
- To generate observable striations, parent masses must move in certain orbits and disintegrate at certain times (Fig. 6), thereby representing only very minor fraction of total population of these objects in comet Hale-Bopp
- Hence, once high repulsive accelerations on parent masses are ruled out as unacceptable, sizable population of boulder-sized (and larger) objects must be assumed to exist, surviving for long periods of time in relative proximity of nucleus (especially large, massive nucleus) in gravitationally bound and/or quasi-bound trajectories
- We find highly satisfactory solutions for striated tail, based on application of six-parameter formalism to this scenario, which, however, are not equivalent to high-acceleration solutions based on three-parameter formalism, as they require different ranges of fragment radiation pressure accelerations
- This scenario has major implications for evolution of cometary nuclei and for strategy of dedicated comet missions in nuclear environment

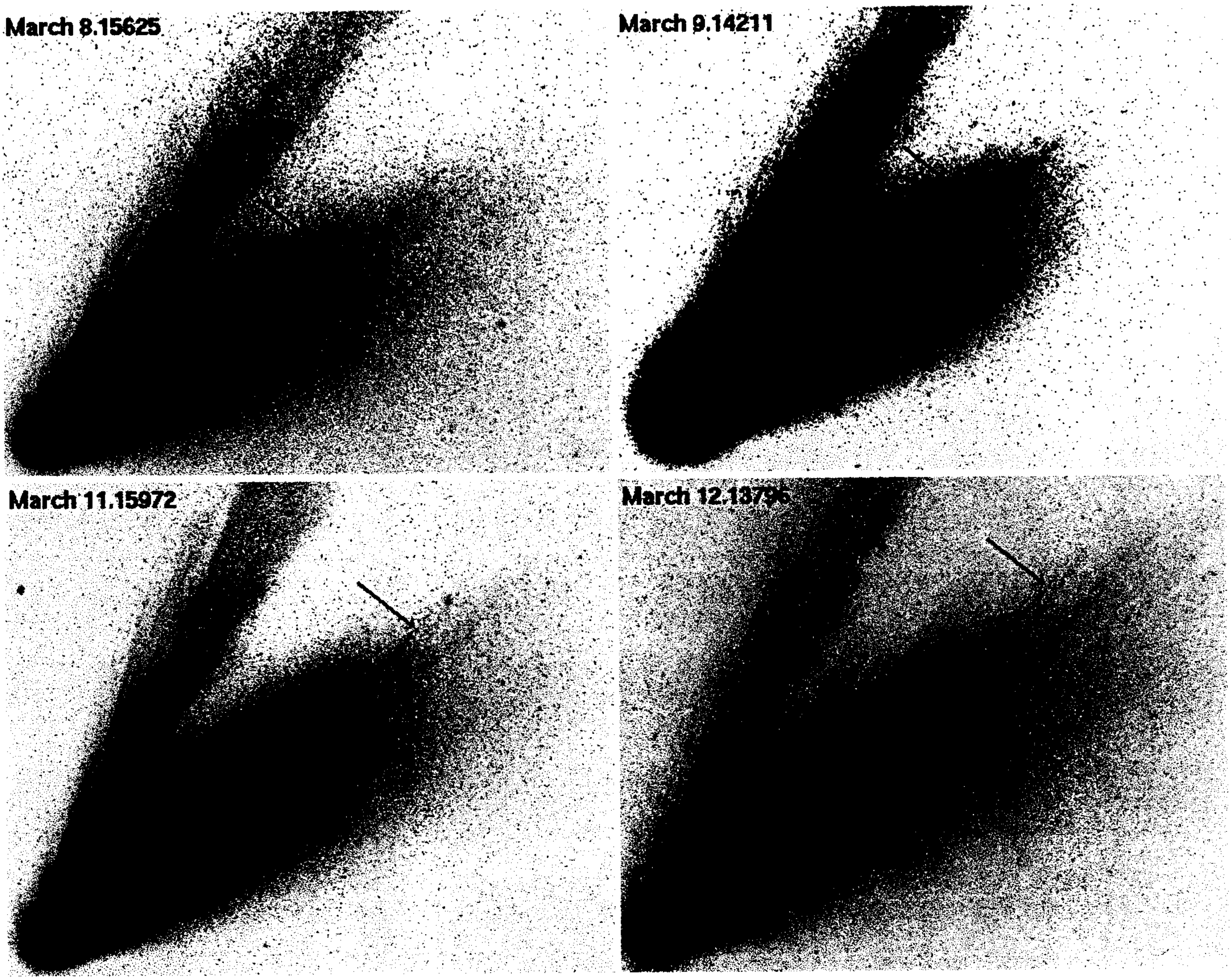


Figure 1

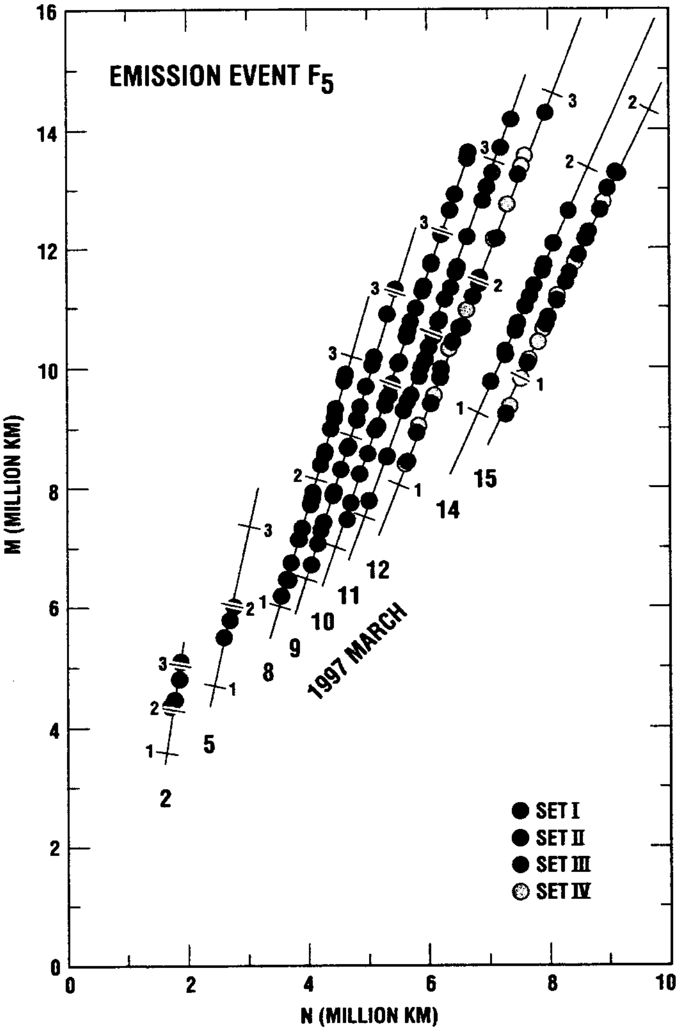

EMISSION EVENT F_5
M (MILLION KM)
N (MILLION KM)
0
2
4
6
8
10
12
14
16
1997 MARCH
2
5
8
9
10
11
12
14
15
● SET I
● SET II
● SET III
◎ SET IV

Figure 2

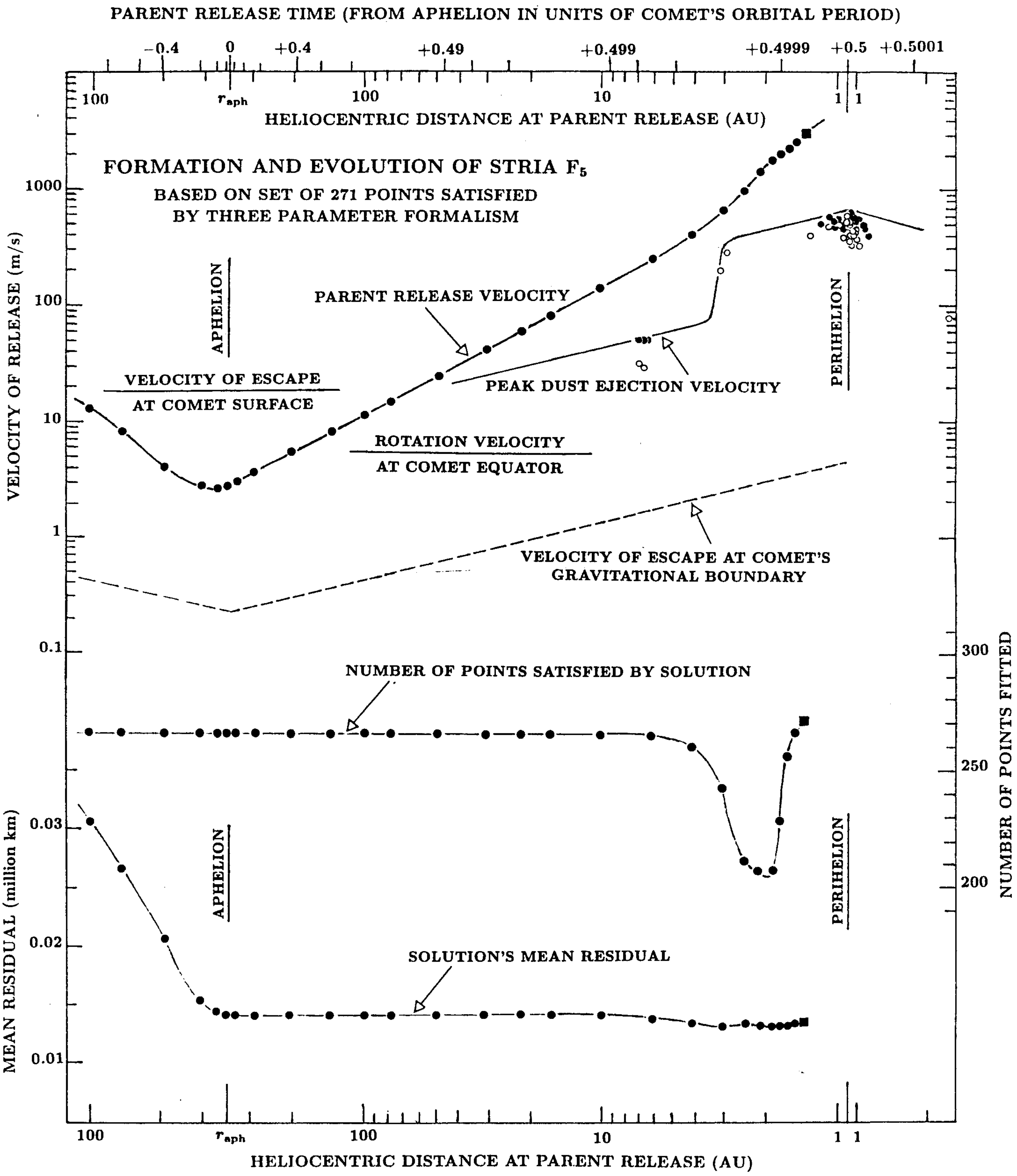
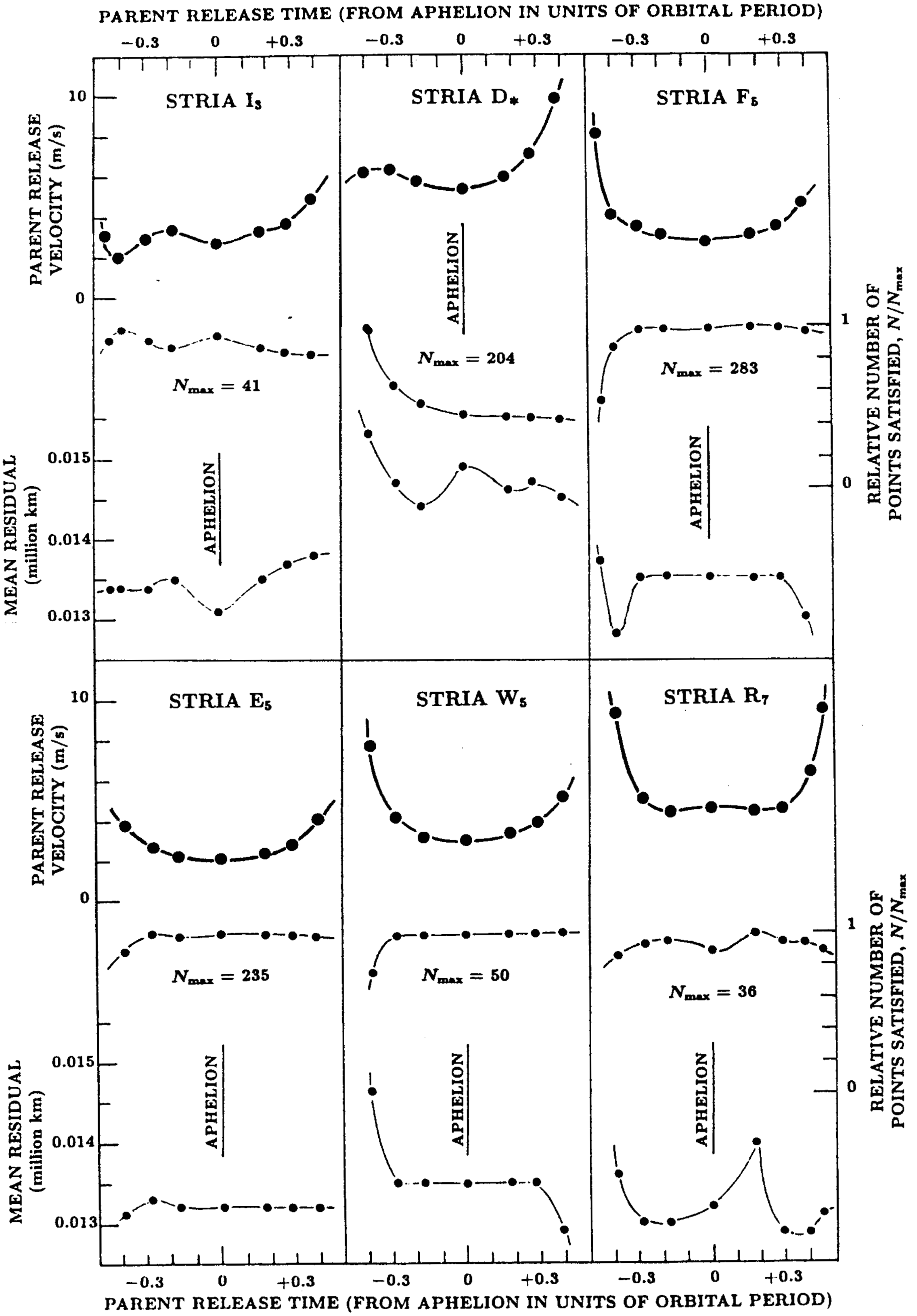

PARENT RELEASE TIME (FROM APHELION IN UNITS OF COMET'S ORBITAL PERIOD)
−0.4
0
+0.4
+0.49
+0.499
+0.4999
+0.5
+0.5001
100
r_{aph}
100
10
1
1
HELIOCENTRIC DISTANCE AT PARENT RELEASE (AU)
FORMATION AND EVOLUTION OF STRIA F_5
BASED ON SET OF 271 POINTS SATISFIED
BY THREE PARAMETER FORMALISM
VELOCITY OF RELEASE (m/s)
1000
100
10
1
0.1
APHELION
PARENT RELEASE VELOCITY
PERIHELION
VELOCITY OF ESCAPE
AT COMET SURFACE
PEAK DUST EJECTION VELOCITY
ROTATION VELOCITY
AT COMET EQUATOR
VELOCITY OF ESCAPE AT COMET'S
GRAVITATIONAL BOUNDARY
NUMBER OF POINTS SATISFIED BY SOLUTION
300
250
200
NUMBER OF POINTS FITTED
MEAN RESIDUAL (million km)
0.03
0.02
0.01
APHELION
PERIHELION
SOLUTION'S MEAN RESIDUAL
100
r_{aph}
100
10
1
1
HELIOCENTRIC DISTANCE AT PARENT RELEASE (AU)

Figure 3



PARENT RELEASE TIME (FROM APHELION IN UNITS OF ORBITAL PERIOD)
−0.3
0
+0.3
STRIA I_3
STRIA D_*
STRIA F_5
STRIA E_5
STRIA W_5
STRIA R_7
PARENT RELEASE VELOCITY (m/s)
10
0
MEAN RESIDUAL (million km)
0.015
0.014
0.013
RELATIVE NUMBER OF POINTS SATISFIED, N/N_{max}
1
0
APHELION
$N_{max} = 41$
$N_{max} = 204$
$N_{max} = 283$
$N_{max} = 235$
$N_{max} = 50$
$N_{max} = 36$

Figure 4

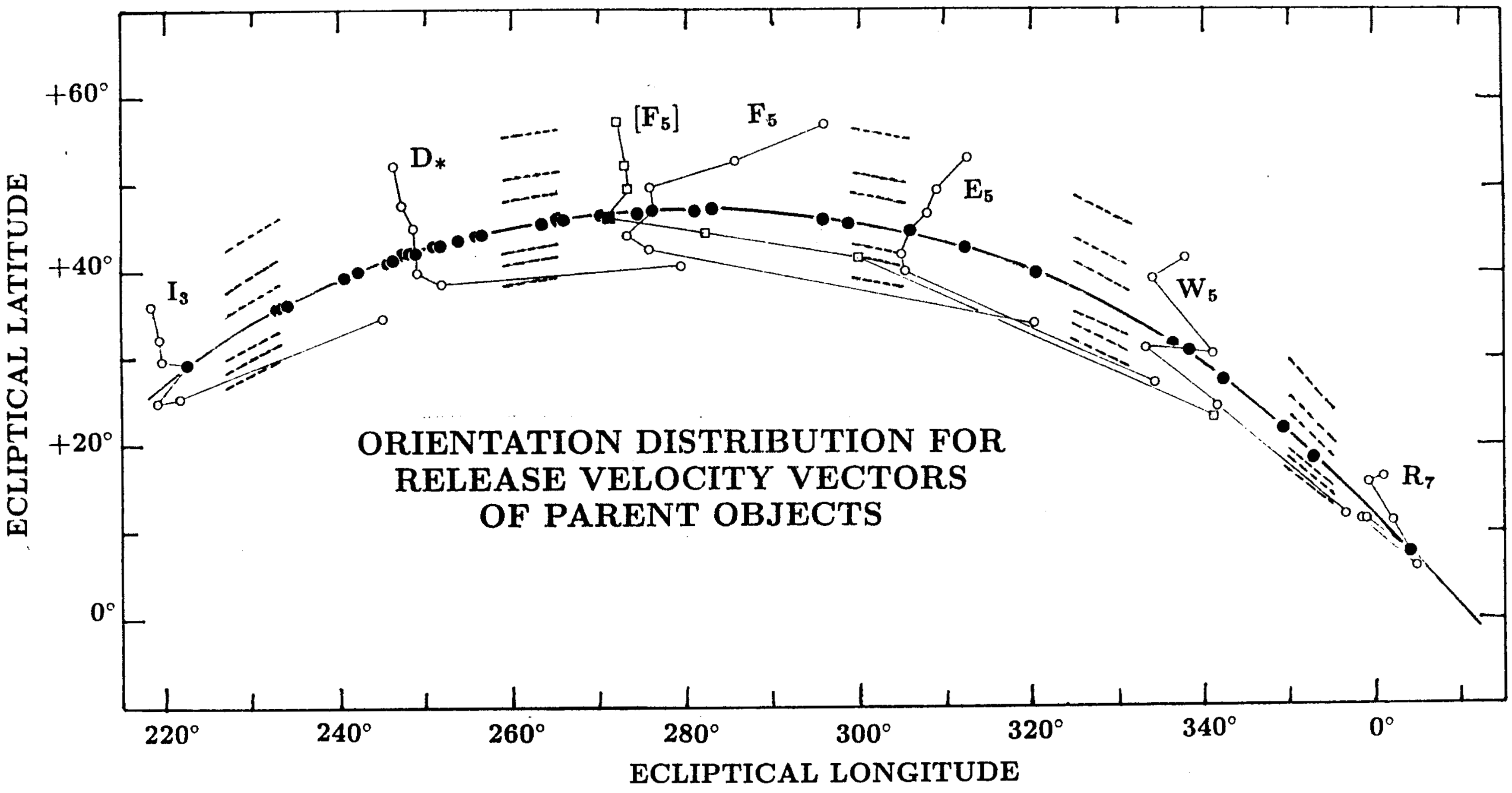

ORIENTATION DISTRIBUTION FOR RELEASE VELOCITY VECTORS OF PARENT OBJECTS
ECLIPTICAL LATITUDE
ECLIPTICAL LONGITUDE
+60°
+40°
+20°
0°
220°
240°
260°
280°
300°
320°
340°
0°
I_3
D_*
$[F_5]$
F_5
E_5
W_5
R_7

Figure 5

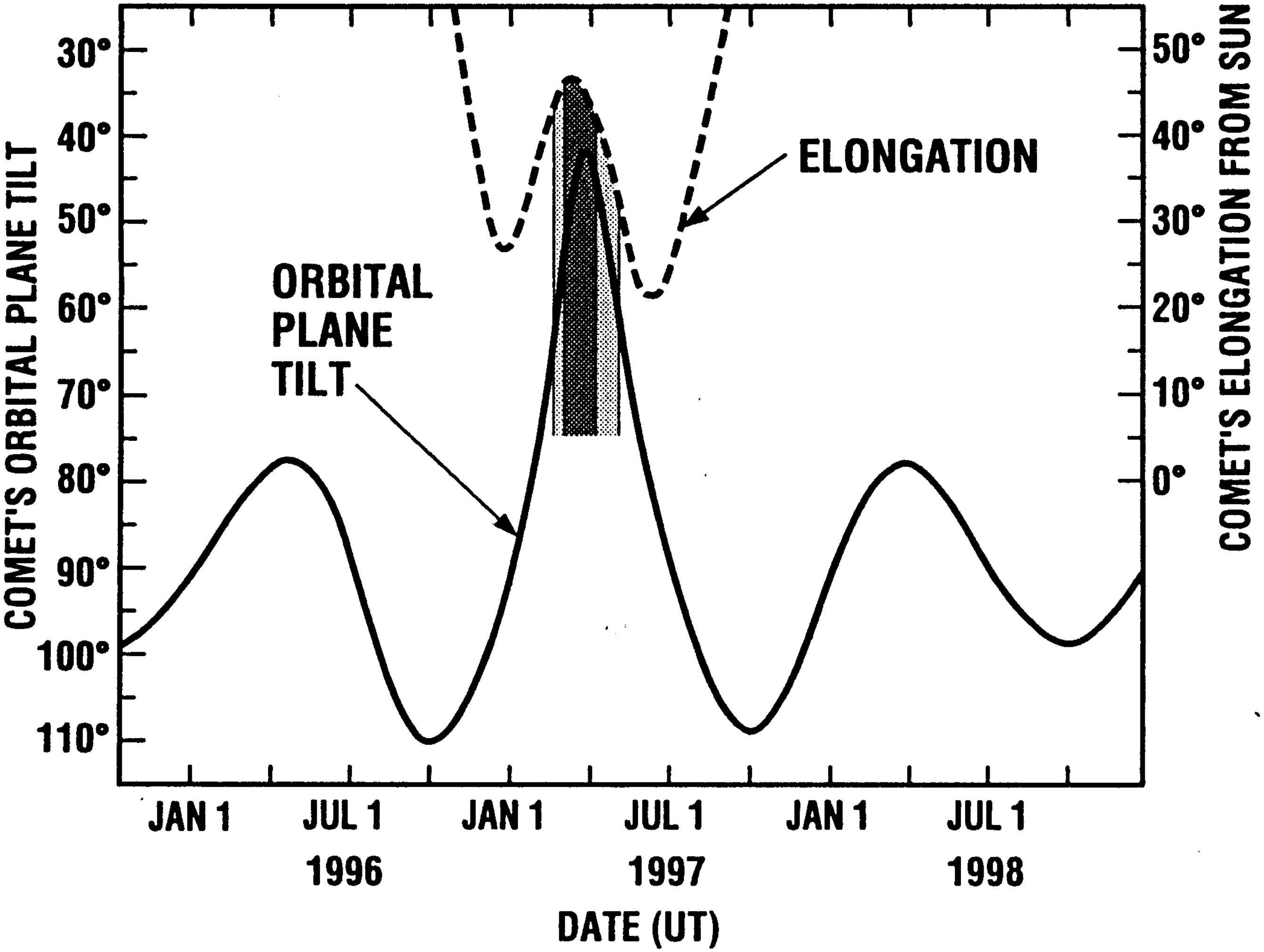

COMET'S ORBITAL PLANE TILT
30°
40°
50°
60°
70°
80°
90°
100°
110°
COMET'S ELONGATION FROM SUN
50°
40°
30°
20°
10°
0°
ELONGATION
ORBITAL
PLANE
TILT
JAN 1
JUL 1
JAN 1
JUL 1
JAN 1
JUL 1
1996
1997
1998
DATE (UT)

Figure 6