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Tomography of a sunward structure in the dust tail of comet 19P/Borrelly*

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Abstract. The observed orientations of a sunward structure (SS) in the dust tail of comet 19P/Borrelly, as it appears in 20 images taken under different projection conditions over a period of 142 days, are compared with the theoretical orientations computed on the basis of two different models: the Spin Model, in which the SS is assumed to be a linear dust jet from an active source close to the cometary pole, pointing about parallel to the nucleus spin axis preceding in the space around a precession axis throughout the relevant time; the Burst Model, in which the observed shapes and orientations of the SS are assumed to be the result of the keplerian motion of dust particles ejected from an active spot located somewhere on the sun-faced nucleus hemisphere during a burst occurred some time before the observations. The best fit of the position angles of the SS linear axis provides two alternative scenarios: the most data consistent Spin Model is characterized by a spin axis preceding from the starting obliquity $I_i = 90^o$ and argument $\Phi_i = 110^o$ to the final $I_f = 120^o$ and $\Phi_f = 80^o$ around the precession axis of $I_p = 74^o$ and $\Phi_p = 62^o$ with a precession period of about 2.5 years; the most data consistent Burst Model is characterized by a burst from an active spot located at a cometographic latitude and longitude of -10^o and 36^o, respectively, occurred about 150 days before perihelion (corresponding to a sun distance of 2.1 AU) with a dust ejection velocity of about 10 m s^{-1}.

Key words: comets: general; 19P/Borrelly

1. Introduction

The aim of this paper is to provide a physical explanation for a Sunward Structure (SS, from now on) observed in the dust tail of Comet 19P/Borrelly during the 1994-1995 apparition. Our starting aim was to apply the synthetic inverse dust tail model (e.g. Fulle 1992) in order to obtain a general scenario of the dust environment of this short period comet. However, soon we faced with a lot of problems, that made impossible to follow this approach. The inverse tail model requires input data sets, each covering a week at most. Therefore, we needed to subdivide the images in several subsets, since they cover a total time interval of 142 days. The first problem was that many subsets were poorly sampled. Moreover, most data were neither calibrated nor filtered, so that they were polluted by coma gas emissions. The few filtered CCD data cover a so small sky field to make impossible any accurate estimate of the sky contribution to the image brightness. Due to the small field, the inner part only of the SS and of the tail was recorded, a fact introducing systematic errors in the model results hard to be quantified. Therefore, it was impossible to build up unique model images of the coma and of the tail of 19P/Borrelly for all input images.

Then, we reduced our goal to a quantitative model of the SS only. However, without realistic tail and coma models, it was impossible to disentangle the light contribution of the coma from that of the SS. In other words, it was impossible to subtract from the input images a quantitative model of the coma in order to obtain the surface light intensity of the SS only (i.e. the required input for a SS quantitative model). Many trials showed that minor changes of the coma brightness slope introduced significant changes of the dust size distribution and ejection velocity best fitting the observed SS. These facts forced us to conclude that most available data do not contain quantitative information on the dust environment of 19P/Borrelly. Nevertheless, they do contain significant morphological information. A striking feature of the SS is the straight linearity of its axis (within the measure uncertainties), so that the best defined data which can be extracted from all available observations regard the position angles of the SS axis. The aim of this paper is to show which results can be extracted from these angles.

The available SS data cover about 90^o of comet orbit true anomaly, so that they can be considered as two-dimensional projections of a three-dimensional object under several perspective conditions. Therefore, our problem can be compared to a classical tomography, which allows us to reconstruct, from the

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* Based in part on data collected at the Asiago Observatory

observed two-dimensional projections, the three-dimensional structure of the object. However, since in this case the total angle covered by the perspective angles is small (from a tomographic point of view), and the data are affected by measure uncertainties, it is necessary to make alternative hypotheses on the three-dimensional shape of the SS. The first one will be named Spin Model (Sekanina 1987). Let us assume that the comet nucleus pole was sun-exposed during all the period covered by the observations, and that close to this pole a small, strongly active dust source was activated by solar heat. The result will be a linear dust jet pointing about parallel to the nucleus spin axis. We point out that the tomographic approach we are following requires that the real structure has in space a well defined motion, such as a spin axis describing a cone around a precession axis with a uniform precession angular speed. Therefore the Spin Model is characterized by five free parameters: the spin axis is defined by the starting obliquity I_s and argument Φ_s (Sekanina 1987), the precession axis by I_p and Φ_p, and the motion of the spin axis around the precession axis by the uniform precession angular velocity ω_p during the relevant time.

The second hypothesis will be named Burst Model. Let us assume that a certain time before observations the comet underwent a burst of a small active spot located somewhere on the sun-faced nucleus hemisphere. Then, the produced dust jet will evolve in space according to the keplerian dynamics of the single dust particles composing the jet. The Burst Model is characterized by four parameters: the longitude and latitude of the burst spot, the time of the outburst, and the dust ejection velocity. In both models, the quoted parameters which determine the SS orientation are the only ones which can be provided by the available position angles. Other parameters, such as the mass loss rate and the size distribution of the dust building up the SS, would determine the surface light intensity of the SS, and would be extracted by quantitative models only of calibrated CCD data.

2. Observations and data reduction

The observations here considered consist of 20 photographic and CCD images (Fig. 1) taken by different observers over a period of 142 days, between 1994 October 20.5 and 1995 March 11.1. Some images were obtained with the 67/92 cm Schmidt Telescope of the Asiago Astrophysical Observatory during free-access time by amateurs. During the relevant time the comet passed at its perihelion point on 1994 Nov. 1.4940 UT, and the Earth crossed the plane of the comet orbit on 1994 Dec. 7.6942 UT. The data concerning the sources of the images and the geometrical circumstances of the observations are summarized in Table 1. The Earth-Sun-Comet geometry is illustrated in Fig. 2. Photograph 7 in Fig. 1 was taken only 11 hours before the date of the Earth's crossing, when the cometocentric latitude of the Earth was of only 0.4^o (see parameter β in Table 1). It clearly shows that the direction of the SS does not coincide with the direction to the Sun (arrow), or the opposite direction, as one may expect for a structure lying in the plane of the comet orbit, when observed under such projection conditions. Really, the difference in position angle of the SS with respect to the Sun-Comet radius vector is of well 13^o, as it results from $PA_{SS} - PA_{RV}$ in Table 1. This means that, at that time, such a structure was stretching outside the plane of the comet orbit, in the cometocentric southern hemisphere.

The line of maximum density (or maximum brightness) of the SS was taken as its axis, denoting the orientation on the sky of such a structure. For the CCD images (well 16 out of 20), such an axis was identified with the straight line connecting the vertices of the lines of equidensity. The measured position angles of the SS (PA_{SS}) and, for comparison, of the Sun-Comet radius vector (PA_{RV}) are summarized in Table 1, together with the apparent length (L), in the projection on the sky, of the observed structure. Measure uncertainties of PA_{SS} are of the order of $\pm 1^o$.

3. The Spin Model versus the Burst Model

In the last two columns of Table 1 we show the results of the SS position angle fits by the quoted models. The Spin Model fits were obtained by covering all obliquities I_s and I_p, and arguments Φ_s and Φ_p with a resolution of 4^o, and the speed ω_p with a resolution of 0.1^o day^{-1}. All the spin vectors were sky projected by means of projection matrices, and the least rms error was searched for. The best fit for all the $O - C_S$ values shown in Table 1 is provided by $I_s = 90^o$, $\Phi_s = 110^o$, $I_p = 74^o$, $\Phi_p = 62^o$ and $\omega_p = 0.4^o$ day^{-1}; the resulting fit rms error is 1.6^o. The fit procedure showed that the spin axis direction is defined within the 4^o of search precision, whereas the precession axis direction strongly depends on the ω_p changes: I_p and Φ_p change of about 15^o when ω_p changes of 0.1^o day^{-1}. The precession period is 2.5 ± 0.5 years and the angle between the spin and the precession axis is about 50^o. The spin axis corresponding to the last observation is characterized by $I_f = 120^o$ and $\Phi_f = 80^o$, so that the active spot (i.e. the nucleus pole) was well sun-exposed during all the time covered by observations. The only doubts the Spin Model leaves regard its physical reliability. In fact, in order to explain the observed SS length, very large ejection velocities are required. For instance, if we assume the largest plausible velocity, i.e. 1 km s^{-1} (Crifo 1991), the dust will reach the SS top ($L \approx 10^5$ km) a day after the ejection. However, only micrometric grains can have these velocities, and after a day the effects of solar radiation pressure over these grains should be clearly visible. Thus, the straight linearity of the SS is an argument against the Spin Model.

The Burst Model fits were obtained covering all the possible longitudes and latitudes of the active spot with a resolution of 2^o, the outburst anomaly with a resolution of 1^o, and the dust ejection velocity with a resolution of 1 m s^{-1}. The keplerian evolution of the single particles composing the resulting jet was then computed for all observations and the three-dimensional SS was sky projected by means of projection matrices. We obtain that the best fit for all the $O - C_B$ values shown in Table 1 was provided by a latitude and longitude of the active spot of -10^o and 36^o, respectively. The spot latitude is referred to the comet orbital plane, whereas the longitude is corotating with the comet anomaly and is counted from the subsolar point: it

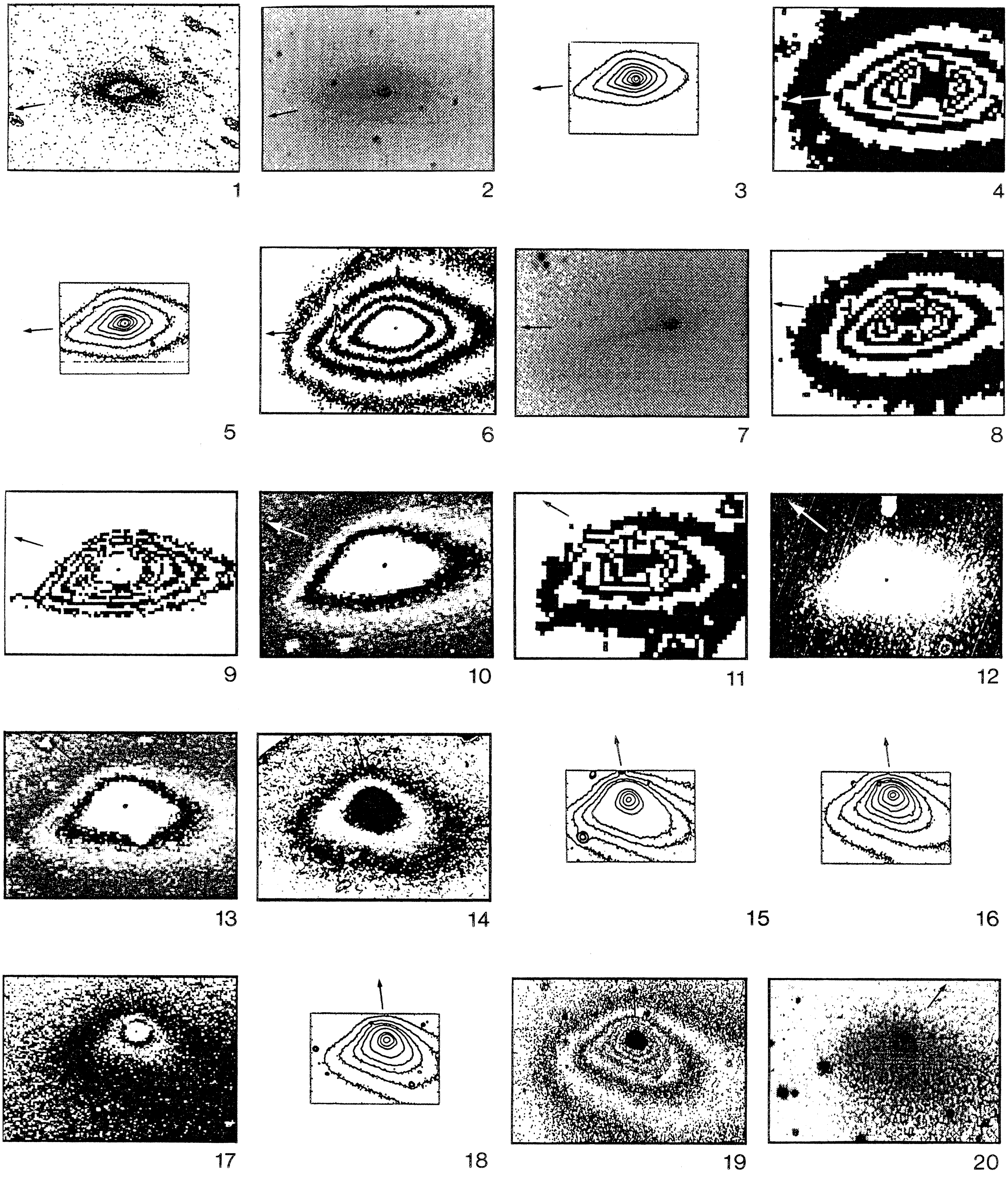

Fig. 1. Panel of the 20 observations here considered. All the images are brought to the same angular scale and oriented so that North is up and East to left. The fields of view are $3.5' \times 5.0'$ for the larger frames, and $2.0' \times 2.8'$ for the smaller ones. Arrows denote the direction to the Sun, i.e., the projection on the sky of the Sun-Comet radius vector.

Table 1. Observational data and fit of the sunward structure. No, serial number of the observation. $Obs.$, Observer: AM - Antonio Milani, 67/92 cm Schmidt Telescope of Asiago Observatory; DS - Dough Snyder; EG - Eraldo Guidolin; GC - Gabriele Cremonese, Asiago Observatory; HM - Herman Mikuz, Ljubljana University; MC - Marco Cavagna, Sormano Observatory; MT - Maura Tombelli, 67/92 cm Asiago Observatory and 20 cm Montelupo Observatory; PP - Petr Pravec, Ondrejov Observatory. UT, time of midexposure, 1994 (N. 1-10) and 1995 (N. 11-20). Δ, r, Earth-Comet and Sun-Comet distances, respectively (AU). β, Earth cometocentric latitude on the comet orbital plane (degrees). PA_{RV}, PA_{SS}, Position Angles of the sky-projected radius vector and sunward structure (degrees). L, sky-projected length of the sunward structure (10^5 km). $O - C_S, O - C_B$, fit of PA_{SS} by the Spin Model and by the Burst Model, respectively (degrees).

No	Obs	UT	Δ	r	β	PA_{RV}	PA_{SS}	L	$O - C_S$	$O - C_B$
1	DS	Oct 20.5243	0.803	1.372	27.9	99.3	90.0	0.4	-0.8	-2.6
2	PP	Nov 6.16	0.698	1.366	22.2	101.8	95.0	0.5	+1.5	+1.3
3	GC	Nov 30.0708	0.620	1.404	6.2	96.0	102.0	0.5*	+0.9	+1.8
4	HM	Nov 30.986	0.619	1.407	5.5	95.5	101.5	0.9	+0.1	+0.9
5	GC	Dec 3.1139	0.618	1.413	3.7	94.1	102.5	0.5*	+0.2	+1.1
6	AM	Dec 4.1271	0.617	1.416	2.9	93.5	105.0	0.7	+2.2	+3.2
7	PP	Dec 7.23	0.618	1.426	0.4	91.1	104.0	0.8	-0.1	+1.0
8	HM	Dec 15.197	0.628	1.454	-6.0	83.8	108.0	-	+0.8	+1.9
9	MC	Dec 23.8905	0.654	1.491	-12.4	73.7	109.0	0.6	-1.2	-0.1
10	MC	Dec 26.899	0.666	1.505	-14.4	69.7	110.0	1.0	-1.0	+0.1
11	HM	Jan 2.849	0.700	1.539	-18.5	59.8	110.0	0.8	-2.4	-1.3
12	EG	Jan 8.01	0.730	1.566	-21.0	51.8	110.0	0.7	-2.8	-1.8
13	MC	Jan 8.793	0.734	1.570	-21.4	50.6	109.0	1.0	-3.8	-2.8
14	AM	Jan 29.0349	0.887	1.689	-26.6	16.3	111.0	0.9	+0.9	+1.6
15	GC	Feb 1.167	0.914	1.708	-26.9	11.1	110.5	0.6*	+1.1	+1.7
16	GC	Feb 2.9111	0.931	1.720	-27.0	8.0	110.0	0.6*	+1.0	+1.6
17	MT	Feb 2.9466	0.931	1.720	-27.0	8.0	110.0	-	+1.0	+1.6
18	GC	Feb 3.0694	0.933	1.721	-27.0	7.7	110.0	0.6*	+1.0	+1.6
19	HM	Feb 5.959	0.960	1.739	-27.0	3.0	110.0	1.0	+1.5	+2.1
20	PP	Mar 11.08	1.327	1.965	-22.1	322.2	120.0	1.0	-0.9	+0.6

* referred to the near-nucleus part of the SS only

turns that the spot was well sun exposed at the outburst. In order to compare the outburst direction, we can convert such a vector to the $I - \Phi$ reference frame (although now such a vector is not a spin). The found spot latitude and longitude correspond to $I = 100^o$ and $\Phi = 139^o$, not far from the spin axis direction of the alternative Spin Model. The most probable burst time is close to 150 days before perihelion, corresponding to a true anomaly of -85^o (see point B_1 in Fig. 2) and a sun distance of 2.1 AU. The dust ejection velocity results $v = 15\ (1 - \mu)$ km s^{-1}, where $1 - \mu$ is the ratio between the solar radiation pressure force and the solar gravitation force. We point out that the obtained dust velocity is able to explain both the straight SS shape and its length. Particles with $1 - \mu = 10^{-3}$ (millimetric grains) provide a SS sky-projected length $L = 10^5$ km, while grains of $1 - \mu = 5\ 10^{-4}$ (centimetric grains) provide $L = 5\ 10^4$ km. Moreover, the ejection velocity of these grains results close to 10 m s^{-1}, a very reasonable value for so large grains. Richter et al. (1991) report velocities close to 10 m s^{-1} for grains with $1 - \mu = 5\ 10^{-4}$ ejected by P/Halley, and velocities of 40 m s^{-1} for $1 - \mu = 10^{-3}$. For $5\ 10^{-4} < 1 - \mu < 10^{-3}$, Neck-Line photometry of Comet Austin 1990V (Fulle et al. 1993) provides velocities of 40 ± 20 m s^{-1}. Although these velocities refer to active comets closer to sun than 19P/Borrelly at the supposed outburst, the comparison is nevertheless significant: we can well assume that the gas loss rate of a short period comet during an outburst is close to that released from large comets in steady conditions. Large grains, just because of their size, are quite unsensitive to the solar radiation pressure, thus explaining the straight shape of the SS. The fit rms error for this model is 1.7^o, close to that provided by the Spin Model.

4. Conclusions

We point out that, in order to definitely discriminate between the proposed models and to further constrain their free parameters, further observations are required, in particular out of the available observation period here considered, in order to improve the total projection angle. Moreover, it is apparent from the proposed fits that the SS was south of the comet orbital plane, not only at the time close to the date of the Earth's crossing (as shown by observation 7 in Fig. 1), but throughout the whole observation period. In the Burst Model context, this is confirmed by the fact that the difference between the true anomaly of the last observation (78.2^o) and the outburst anomaly (-85^o) is less than 180^o. Thus, at the time of the last observation the SS had not yet reached its second node, at which it should have necessarily passed to the north of the comet orbital plane. Therefore, observations five months before the comet perihelion would have allowed us to check if the SS was really absent (indeed, the burst should have not yet occurred), whereas observations after March 1995 would have allowed us to check if the SS really turned from south to north of the comet orbital plane. Unfortu-

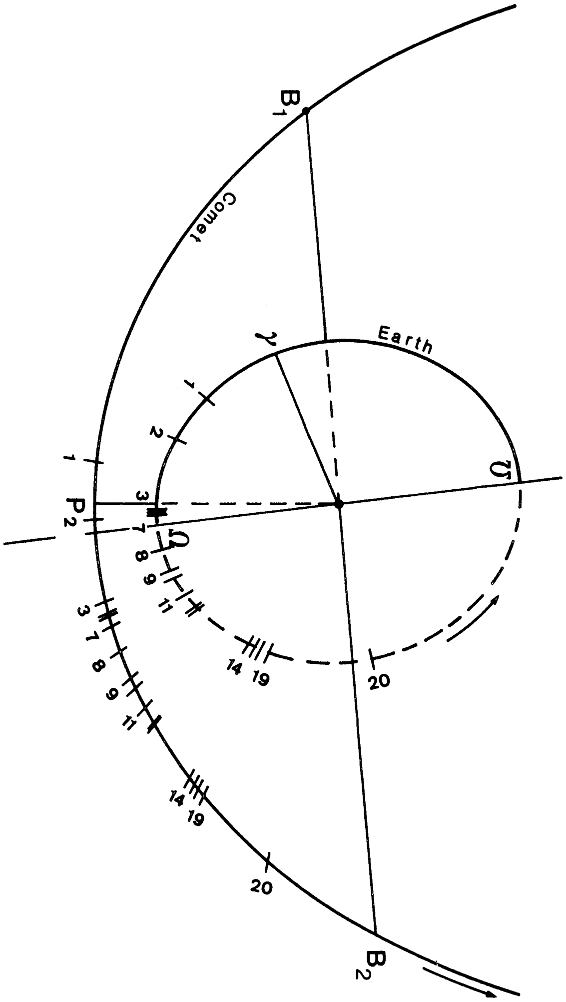

Fig. 2. Earth-Sun-Comet geometry as seen from the north pole of the comet orbit. Numbered dashes represent the positions of the Earth and of the comet with reference to the observation No in Table 1. Avoiding to embarass the figure, only a few positions are numbered. P denotes the perihelion point of the comet whereas point B_1 denotes the position of the comet at the time of the supposed outburst, which gave rise to the observed SS in the Burst Model. B_1B_2 is the nodal line of the orbits of the dust particles ejected from the nucleus at point B_1.—

nately, it will be impossible to find observations more than 4.5 months before perihelon, since the comet was recovered only on 12 June 1994 (Kilmartin & Gilmour 1994). On the other hand, observations after March 1995 are lacking. In the Spin Model context, the SS should have been placed north of the comet orbital plane just before the first available observation, when the spin axis obliquity was close to 90^o (and was increasing therein).

Future work, devoted to SS quantitative models applied to calibrated CCD images, might allow us to check which of the proposed models is physically most plausible. However, it will be impossible to check if the quantitative model fitting the few filtered and calibrated images will be consistent with all the available images, i.e. with the whole SS time evolution. The uncertainties of the burst anomaly suggest an upper limit for the burst duration of about a week. Since it occurred quite close to the Sun (2.1 AU), such a duration is consistent with the production of large dust masses, possibly driven by both water and CO, so that a SS quantitative fit too seems plausible. Further constraints to the Spin Model parameters might come from future direct observations of the 19P/Borrelly nucleus, since at least one of the proposed axes should be close to a maximum inertia axis of the nucleus. It is interesting to note that the proposed precession allows the active spot to be sun-exposed for more than half orbit (the usual constraint for a non-preceding spin axis). In particular, activation of the pole spot is possible from a starting anomaly of about -100^o to a final anomaly of about 170^o; however, the large uncertainties affecting the precession period do not allow us either to better constrain these limits, or to extrapolate a realistic configuration of the 19P/Borrelly nucleus spin state back to previous perihelion passages, in order to constrain the proposed Spin Model with possible past observations of other similar Sunward Structures.

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