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SOME CHARACTERISTICS OF THE SOLAR WIND INFERRED FROM THE STUDY OF SODIUM EMISSION FROM COMETARY NUCLEI

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Abstract. Seventeen comets, having information on sodium D-line emission during their apparition, have been studied. The heliocentric distances corresponding to the sodium emission commencement or termination epoch are found to have a dependence on the phase of the solar cycle. For comets appearing during a solar maximum the sodium emission is detectable out to greater distances than, for the comets appearing during solar minimum. The sodium emission is also found to depend on heliographic latitude of the comet. It is concluded that the spatial properties of the solar wind during a solar maximum and minimum are responsible for the observed dependence.

1. Introduction

It is generally known that comets display bright sodium D-line emission when their heliocentric distances are less than 0.8 AU. The spectroscopic observations of Comet Ikeya-Seki 1965 VIII (Bappu and Sivaraman, 1967, 1969) show that the sodium emission from the nucleus ceased to exist beyond $r = 0.595$ AU. Since this was far below the average heliocentric distance over which a comet exhibits sodium emission, we examined the literature for details on the incidence and duration of the phenomenon. The information we have collected is very sparse, but it has features of such considerable interest that we feel justified in attempting some conclusions on the basis of the very limited data available. We present these results in the hope that they will serve to indicate a new possibility of exploration of solar wind characteristics by yet another kind of cometary observation.

2. Observations

The available information on sodium emission in comets relevant to this study is summarized in Table I. We present here details pertaining to seventeen comets. We indicate in this list either the first day of the incidence of sodium emission or the last day it was seen after perihelion passage. The column entitled heliocentric distance is the value of the parameter for such a first or last day. We have also calculated the heliographic latitude of the comet on the date of interest.

The observations are not all of equal weight, as a consequence not only of the difficulty of making continuous and detailed observations of these rare visitors, but also because of the varied instrumentation used for detection. There are more numerous observations available of sodium emission in the era when such observations were made with a visual spectrometer than when the photographic plate became the standard radiation detector. The visual observations, however, are quite reliable, because when

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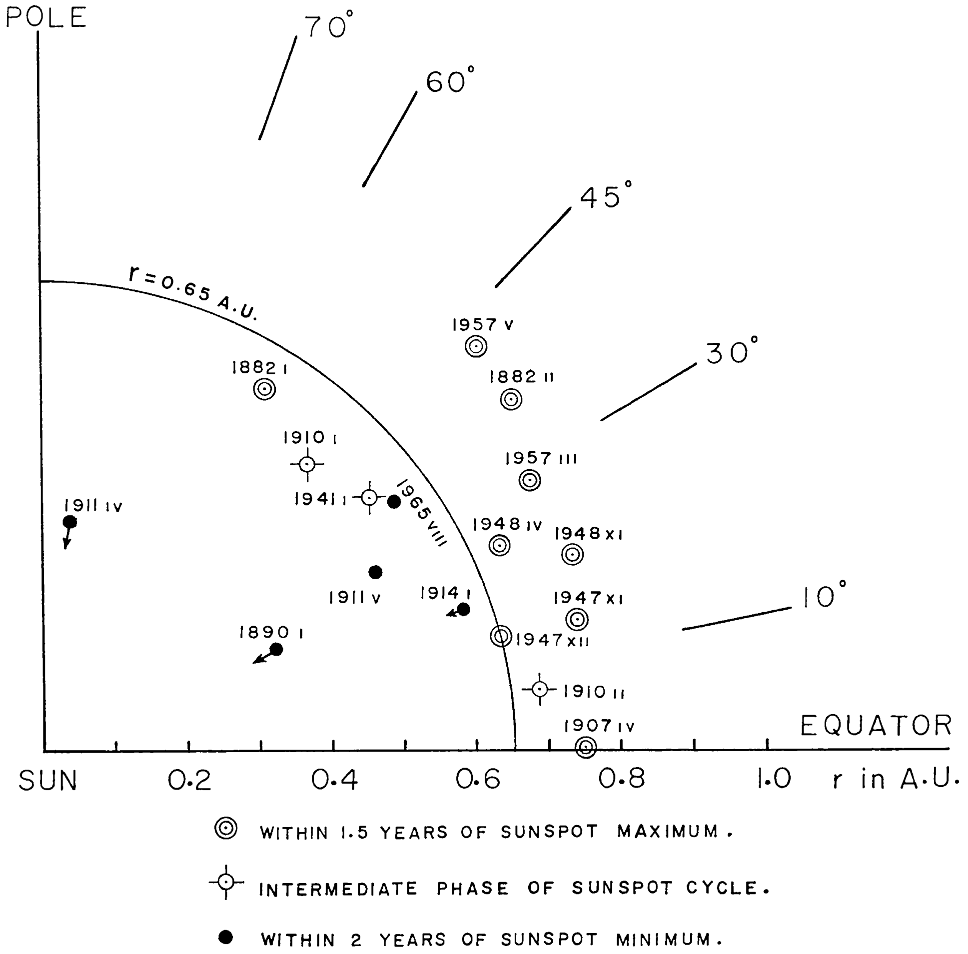

Fig. 1. Heliocentric positions corresponding to the D-line commencement or termination epoch.

sodium emission is present, the monochromatic nature of the radiation confines it to a sharp point of high intensity, unlike the molecular Swan bands, and hence makes detection inescapable to any experienced observer. Three of the comets of Table I, Comets 1890 I, 1911 IV, and 1914 I have extremely meagre information. The dates given in column (6) only serve as upper limits to the heliocentric distances before sodium emission was seen in them. However, we have included them in our discussion since they add additional stability to our findings.

3. Discussion

We plot in Figure 1, the heliocentric distances corresponding to the D-line commencement or termination epoch and the corresponding heliographic latitudes. The comets are classified into three categories depending on the phase of the cycle of solar activity when they made their appearance. The family of 'maximum' comets are those that have had their perihelion passages within 1.5 years of sunspot maximum. The 'minimum' comets are those that have appeared within 2 years of a sunspot minimum while the third category contains the comets that had the times of perihelion during the intermediate phases of the sunspot cycle. On this (r, θ) diagram one striking

TABLE I

Available data on sodium emission in comets

No.	Comet		Difference in years between epoch of observation and nearest solar maximum or minimum		Date of observation Na-emission first seen/last seen	Heliocentric distance in AU	Heliographic latitude
	Name	Designation Perihelion passage	max.	min.		r	θ
1	2	3	4	5	6	7	8
1	Wells	1882 I June 11.0	−1.5	+3.5	May 27	0.586	57° 55′
2	Brilliant Comet	1882 II September 17.7	−1.1	+3.9	October 7	0.807	36° 10′
*3	Borrelly	1890 I January 26.98	−4.1	+0.4	January 19	0.35	23° 24′
4	Daniel	1907 IV September 4.5	+0.8	−5.8	August 10	0.75	0° 12′
5	Day light Comet	1910 I January 17.6	+3.1	−3.5	January 30	0.54	46° 58′
6	Halley	1910 II April 20.2	+3.3	−3.3	May 7	0.69	6° 58′
*7	Beljawsky	1911 IV October 10.8	+4.8	−1.8	October 13	0.32	83° 12′
8	Brooks	1911 V October 28.2	+4.8	−1.8	October 20	0.52	28° 18′
*9	Zlatinsky	1914 I May 8.9	−3.2	+0.8	May 20	0.61	18° 40′
10	Cunningham	1941 I January 16.2	+3.6	−3.3	December 31	0.57	37° 40′
11	Encke	1947 XI November 26.3	+0.1	−6.7	November 1	0.76	13° 42′
12	Southern Comet	1947 XII December 2.6	+0.3	−6.5	December 20	0.65	−13° 51′
13	Honda-Bernasconi	1948 IV May 15.9	+0.7	−6.1	June 6	0.69	23° 43′
14	Eclipse Comet	1948 XI October 27.4	+1.2	−5.6	November 20	0.78	−20° 09′
15	Arend-Roland	1957 III April 8.0	−0.5	+2.8	May 3	0.77	29° 11′
16	Mrkos	1957 V August 1.4	−0.1	+3.2	August 30	0.82	42° 40′
17	Ikeya-Seki	1965 VIII October 21.2	−3.0	+1.0	November 3	0.595	−35° 20′

Notes on pages 499–500

Notes to Table I

* Comets with meagre information.

1. Comet 1882 I – Sodium emission first seen on May 27 at Dun Echt (*Monthly Notices Roy. Astron. Soc.* **43** (1883) 198). The intensity increase seen on May 28 suggests that the emission may not have existed on May 26 at $r = 0.616$. A firm observation at Greenwich (*Monthly Notices Roy. Astron. Soc.* **42** (1882) 412) indicates that there was definitely no sodium emission on May 22 ($r = 0.729$). Konkoly (*Observatory* **5** (1882) 291) found no evidence of D-line emission on May 25 ($r = 0.645$).
2. 1882 II – The sodium lines were last observed on October 7 ($r = 0.807$) (*Vogel Astron. Nachr.* **103** (1882) 279). (Vsekhsvyatski, *Physical Characteristics of Comets*, 1964, p. 267.)
3. 1890 I (Borrelly) – Backhouse (*Observatory* **13** (1890) 90) saw with a spectroscope no emission other than the Swan bands at $r = 0.43$.
4. 1907 IV – A spectrogram obtained by Slipher (*Lowell Obs. Bull.* No. 52 (1911)), on August 10, 1907, ($r = 0.75$) "shows bright D along with the carbon bands and the continuous spectrum". The intensity of the emission suggests that it may have been present even two to three days earlier ($r = 0.82$).
5. 1910 I – The D-lines were last observed on January 27. Albrecht (*Lowell Obs. Bull.* No. 174 (1910) 183) finds D_2 of considerable strength on January 27 and absent on a well exposed spectrogram of January 30 ($r = 0.54$).
6. 1910 II – Slipher's spectra (*Lowell Obs. Bull.* No. 52 (1911)) which cover the interval up to May 31 show conclusively that no sodium emission was seen with certainty after May 7. The D-line behaviour of this comet was quite unusual. Greatest brilliancy was reached ten days after perihelion passage. It was first recorded on April 16 ($r = 0.60$). On April 17, 18 and 20 well exposed spectra failed to show it. The next recording of bright D was only on April 29. During the period April 30 to May 7 it fluctuated in intensity having been as bright on May 6 as it was on April 30, with a sudden fading thereafter of May 7.
7. 1911 IV (Beljawsky) – Konkoly (*Astron. Nachr.* **190** (1911) 42) observed this comet at $r = 0.32$ with a spectroscope and reports no sodium emission even though the (0, 1) C_2 system was very bright.
8. 1911 V – Bright D-lines seen on October 22 (*Lick Obs. Bull.* No. 209 (1912) 12). No mention is made of sodium emission on a spectrum obtained on October 18 ($r = 0.55$). The intensity of emission on October 22 suggests that it may have been present even one or two days earlier ($r = 0.52$).
9. 1914 I (Zlatinsky) – Konkoly (*Astron. Nachr.* **202** (1916) 143) reports no sodium emission at $r = 0.61$. He has used for this observation the Hα, D, Mgb and Hβ lines of Venus as reference lines.
10. 1941 I – Swings and Haser (*Atlas of Representative Cometary Spectra*) remark that the D-lines were last seen at $r = 0.57$).
11. 1947 XI – A spectrum obtained at $r = 0.76$ is reproduced on Plate XVI of the Swings and Haser atlas. This spectrum is heavily superposed with twilight emission but we infer the presence of sodium emission in the comet by a comparison of the intensities along the slit of both the D-line and the 6300 airglow emission line.
12. 1947 XII – Swings and Page (*Astrophys. J.* **108** (1948) 526) have observed D-line emission until $r = 0.65$. The next available spectrum in the visible region is at $r = 0.98$ which is at too large a heliocentric distance to show up sodium in emission. As in Halley's comet there appears to be intensity fluctuations in the sodium emission since it is more intense at $r = 0.65$ than at $r = 0.59$. The emission would have lasted in our opinion until $r = 0.7$ or more, but in the table we give $r = 0.65$ as the last definite observation.
13. 1948 IV – Fehrenbach and Courtes (*Ann. Astrophys.* **12** (1949) 66) list a weak line of intensity at 5893.4. This can be seen well in their reproduction of the spectrogram of June 6 ($r = 0.69$). This is presumably caused by sodium emission.
14. 1948 XI – Jose and Swings (*Astrophys. J.* **111** (1950) 41) have spectra of the nucleus and coma for $r = 0.73$, 0.78, 0.90 and greater heliocentric distances. Sodium emission was definitely seen at $r = 0.73$, and at 0.78. At the latter heliocentric distance the emission had concentrated to the nucleus. The D-line emission vanished between $r = 0.78$ and 0.90. From an examination of the spectrum of this comet in the visual region as seen in the Swings and Haser Atlas we infer that it could have existed at most for only a day or two corresponding to $r < 0.83$.

15. 1957 III – Fehrenbach, Haser, Swings and Woszczyk (*Ann. Astrophys.* **20** (1957) 145) record the presence of D-line emission until $r = 0.77$.
16. 1957 V – Greenstein and Arpigny (*Astrophys J.* **135** (1962) 892) have reproduced in their Figure 1 a low dispersion spectrum of this comet which shows bright sodium-emission at $r = 0.82$. The intensity is such that it would have been present for a few days more.
17. 1965 VIII – D-line behaviour is described by Bappu and Sivaraman (*Kodaikanal Obs. Bull.* No. 178 (1967)). No sodium emission was seen beyond $r = 0.595$.

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feature is that the 'maximum' comets display the sodium D-lines in emission out to greater heliocentric distances than the 'minimum' comets. The brilliant daylight Comet 1882 II and Comet Mrkos 1957 V are two of the best cases in our list where sodium was seen to the farthest heliocentric distances of 0.81 AU and 0.82 AU respectively. In the case of Comet 1957 V the emission lines were of appreciable intensity even at the listed value of r. It is, therefore, very likely that the sodium emission would have existed even at much greater values of r. Of the three 'intermediate' comets both comets 1910 I and 1941 I resemble completely the 'minimum' comets in the sodium emission behaviour. The third object Comet 1910 II displayed sodium emission to $r = 0.69$ which places it near the inner boundary of the zone in r of the 'maximum' comets. This comet (Halley's) has a very good coverage of observations in the yellow-orange region of the spectrum. The observations reported by Bobrovnikoff (1931) show violent changes in the sodium intensity (see notes to Table I) so much so that sodium emission was even absent for a smaller value of r! An examination of Kodaikanal calcium spectroheliograms showed no abnormal solar activity within the comet's view during this entire period.

The satellite observations of solar wind velocities in the region of the ecliptic indicate a dependence on phase of the solar cycle. The Mariner 2 results have shown a range in the value of the daily average velocity between 306 km/sec and 842 km/sec. The latter value is connected with the active region complexes, that shoot hot, high velocity plasma streams into a quiet solar wind medium of velocity near 320 km/sec. We believe that the sodium emission phenomenon is intimately connected with the velocity dependence of the solar wind on the solar cycle. The interaction with the comet of the solar wind can be in the form of a charge transfer and a momentum and energy transfer. The actual mechanism involving the release of sodium atoms from the parent molecules of the cometary matrix is not clear at present. Hence, the energy and momentum transfer either from plasma instabilities or direct collisions near the nucleus would be the principal source of the sodium release. In making such a conjecture on the mechanism of sodium release, we have ignored the possibility of an interaction between the magnetic fields associated with the solar wind and the cometary constituents. We believe that while magnetic fields can play a significant role in the acceleration phenomena observed in Type I tails, their contribution towards the actual sodium release would be negligible.

When, therefore, a comet makes its appearance, the abundance of free sodium atoms released from the cometary ices would have a heliocentric distance dependence according to the phase of the solar cycle.

A second feature of Figure 1 is the heliographic latitude dependence of the sodium emission. The 'maximum' comets display D-line emission to greater distances in the heliographic latitude range 0°–45° than in the 45°–90° zone. The behaviour manifests even in the 'minimum' and 'intermediate' comets. We find that even at minimum the r values, at low latitudes when sodium emission is last seen, range between 0.5 and 0.6 AU. The 'maximum' Comet 1882 I had an r value of 0.59 AU at $\theta = 58°$ while in the case of the 'minimum' Comet 1911 IV which had $\theta = 83°$, no sodium was detected even at $r = 0.32$. The observations of comet 1882 I are very decisive on the date of actual appearance of the emission. The emission was first seen with certainty at $r = 0.586$. It was definitely non-existent at $r = 0.645$ and $r = 0.729$. The intensity increase immediately after discovery was such that an observation if made on the previous day ($r = 0.616$) would have revealed no emission. The single observation of comet 1911 IV is by a very experienced cometary spectroscopic observer who found the (0, 1) C_2 system bright and hence would definitely have detected any sodium emission, if it existed.

Even the 'intermediate' comets, especially Comet 1910 I, show the heliographic latitude dependence; its well determined last day of visibility of sodium emission comes about at a heliocentric distance smaller than in the case of Comet Ikeya-Seki 1965 VIII.

4. Conclusions

We conclude that the greatest distance to which sodium emission can be seen for a cometary apparition at high heliographic latitude is much less than the value for comets having θ values between 15 and 40°. We have only one case, comet 1907 IV, that has a very low heliographic latitude. The intensity observations imply that the emission would have existed even to $r = 0.82$, in which case the latitude range 0–40° appears to cause sodium emission to the farthest heliocentric distance values.

The limited sample we have admits the possibility that the few comets discussed above to show a latitude dependence may have been exceptional in their behaviour. However, all our reasoning depends on the assumption of a typical cometary matrix that shows little variation from comet to comet. If then, we associate the sodium emission with the kinetic energy characteristic of the solar wind, the behaviour of the high latitude comets 1882 I, 1910 I and 1911 IV can be explained only if we assume a smaller velocity of the solar wind at high heliographic latitudes than near the solar equator and most certainly in the latitude belt of maximum solar activity. This latitude dependence also rules out the possibility of radiative dissociation by ultra-violet and X-radiation as a primary mechanism of sodium release from the comet.

References

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