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Chaos in cosmic rays: A fractal wave model

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Abstract. Continuous observations of cosmic ray air showers with average primary energy of 3×10^{14}eV have been made in five different stations in Japan since five years ago. The time sequence of air shower arrival time intervals (ASATIs) containing several hundreds events were analysed for finding some fractal dimension as the chaos signature in short range series of ASATIs. Nearly 100 candidates of the chaotic ASATIs were found. The average fractal dimension is 3.7. The frequency distribution of the central right ascension of the candidates has two peaks around 4 and 20 hour which are the direction of the Galactic plane. The time variation of the chaotic feature had a quasi periodic behaviour, though the low fractal dimension is not obtained due to the mixture of the noise except the candidates. It is supposed that the periodic behaviours of the chaotic ASATIs come from the periodic observation, with the rotation of the earth, of the chaotic cosmic rays that have fractal wave structure, arriving from a non-linear accelerator like supernove remnant which is not so far from solar system.

1 Introduction

Air shower arrival time intervals(ASATIs) are normally considered to be random, and actually that is true for most of them. However, low correlation dimension have been found for several hundreds series of ASATIs with average primary energy of 3×10^{14}eV (T.Kitamura et al.,1997 and W.Unno et al.,1997). Continuous observations of cosmic ray air showers have been made in five different stations in Japan since five years ago to confirm the chaotic feature of ASATIs and the arrival direction (S.Ohara et al.,2001). In the present paper, we reconfirm the chaotic feature of the cosmic rays and the arrival directions which are observed in five stations until Feb.2001 and a model is proposed to explain the cosmic ray chaos and the feature.

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2 Observation and Analysis

The ASATIs have been observed since Jan.1994 at Kinki University, since Jul.1996 at Nara University of Industry, since Sep.1996 at Okayama University and Okayama University of Science and since Nov.1998 at Hirosaki University, using $5 \sim 8$ plastic schintillation counters array. The Nara University of Industry is located about 11km south-east from Kinki University(Osaka). Okayama University is located about 153 km west from Kinki University. Okayama University of Science is located about 152km west from Kinki University. Hirosaki University is located about 787km north east from Kinki University. The total number of the observed ASATIs were about 3500k events until Feb.2001 at five stations, though the average event rate vary (about $0.3 \sim 0.9$ events/min) with stations. The frequency of air shower triggered in interval 10 min. obey well the Poisson distribution, though lately air shower clusters were mostly observed around 5 and 20 hour of the right ascension (T.Konish et al.,2001).

2.1 Fractal Dimension Analysis

The fractal dimension analysis is executed for every 300 ASATIs stepping the first event by 10 events on the series of ASATIs among 3500k events by use of the Grassberger-Procaccia method (P.Grassberger et al.,1983). At first, 11-dimensional vector points, constructed from the original ASATIs, are embedded in 11-dimensional embedding space. The total number of pairs of vector points $C_{11}(r)$ which are between the mutual distance r is calculated in the next place. Then, the fractal dimension $D_{11}(r)$ is given by $d \ln C_{11}(r)/d \ln r$. The chaotic 300 ASATIs are detected so that the constancy of D_m-value is less than 5 as $2D_m + 1 < 11$ and the range of the constancy is larger than 1/5 of the total range of $\ln r$ as shown in Figure 1.

The fractal dimension is estimated for partial 150 or 200 ASATIs which play dominant role for the chaotic feature and have the saturation point of D_m value by the increasing of the

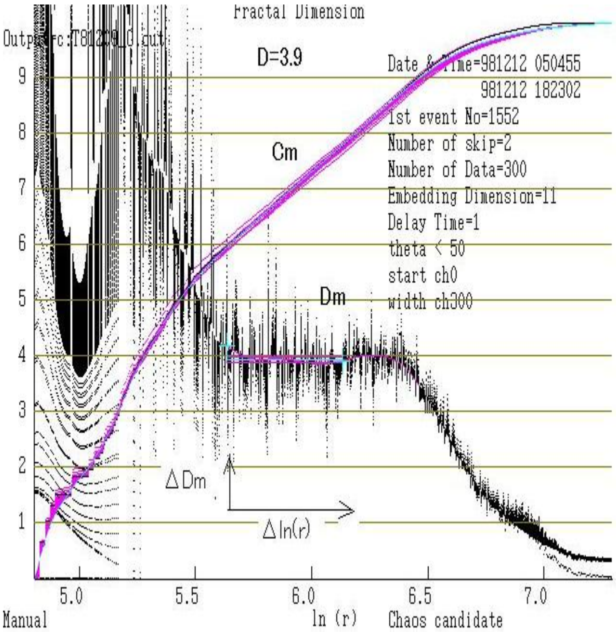

Fig. 1. The diagram of the fractal dimension analysis for the chaotic ASATIs.

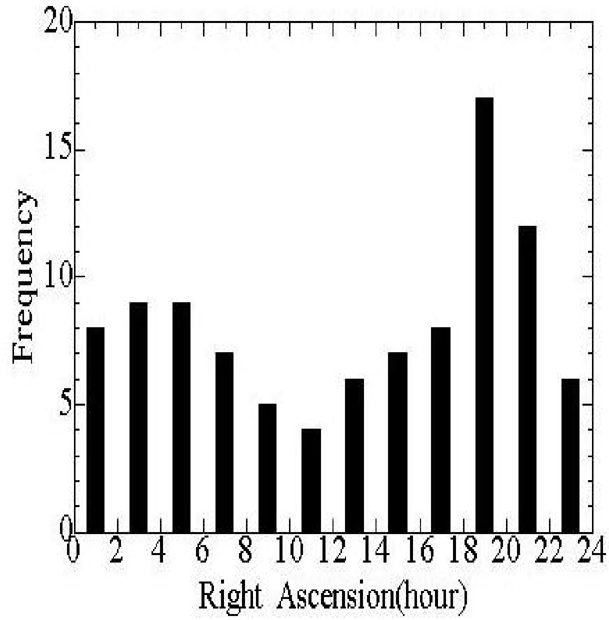

Fig. 2. The frequency of the central right ascension of chaotic ASATIs.

embedding dimension because of effective exception of the random part in original chaotic 300 ASATIs.

Table 1 gives the detected cases of the chaotic ASATIs covering over 300 events observed at the four stations in 2000. The first column in these tables shows the date and time of the first event of chaotic ASATIs, the second column shows the fractal dimension, the third column shows the central right ascension of the dominant 150 or 200 ASATIs, the fourth column shows the duration time(hours) of each case.

The total number of the chaotic ASATIs, detected since 1994, are 97 cases. They are all passed the surrogate data test to confirm not to be a colored noise (J.Theiler,1991). The frequency of the simultaneous detection of the chaotic ASATIs between two different stations is once per two years. This is not necessarily significant value for the coincident detection of the chaotic cosmic rays at present. The appearence of the cluster found by T.Konishi et al. has no concerning with the chaotic ASATIs. On the contrary, the sequence of large ASATI plays much important role than the small ASATI as confirmed by a simulation. Figure 2 shows the frequency distribution of the central right ascension of the dominant ASATIs among the chaotic ASATIs for 97 chaotic cases. It has two broad peaks around 4 and 20 hour. The right ascensions in Figure 2 except 4 ± 1 and 20 ± 1 hour may be estimated shifting from 4 and 20 hour because the central ASATIs not necessary play a central role for the chaotic feature. However the right ascensions around 11 hour is assumed to be significant because it separate enough from 4 and 20 hour, though the frequency of the chaotic ASATIs centered around 11 hour is low as shown in Figure 2.

Table 1. The Detected Chaotic ASATIs in 2000.

Date D.M.H	Fractal Dimens.	Right Ascen.(h)	Durat.(h) of Chaos
Kinki University			
08.Jan.00	3.6	4.6	43
17.Jun.03	3.7	21.4	59
Nara University of Industry			
15.Jul.02	3.5	21.1	31
28.Aug.15	4.1	4.6	22
28.Oct.17	2.2	18.8	36
Hirosaki University			
28.Jun.12	3.9	5.4	20
02.Nov.16	3.5	18.1	25
Okayama University			
18.Jan.18	4.1	18.1	23
16.Nov.18	3.9	18.9	15

2.2 The Time Variation of the Slope of D_m Curve During Several Days.

The time variation of the *Slope* ($\Delta D_m/\Delta \ln r$, see Figure 1) of 150 or 200 ASATIs is calculated for the data obtained during several days including the chaotic ASATIs at every station. The typical results are shown in Figure 3 and Figure 4.

The time variation of the $Slope$ of D_m-curve frequently shows quasi periodic troughs around the right ascension 4 and 20 hour, though many ASATIs don't give the low fractal dimension due to the mixture of the noise except the chaotic ASATIs. This result corresponds well to the result shown in Figure 2. Even the ASATIs out of the chaotic ASATIs show the quasi periodic behaviour of the time variation of the $Slope$ which has no zero value. Then, the chaotic cosmic

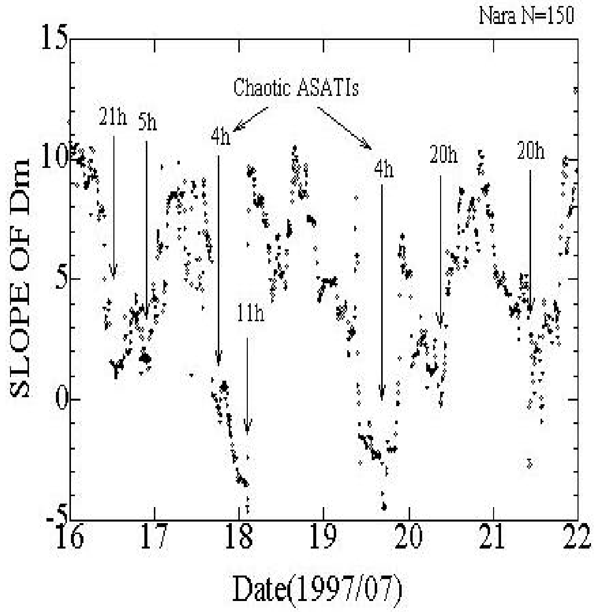

Fig. 3. The time variation of the *Slope* of the D_m-curve of ASATIs observed at Nara array in Jul.1997.

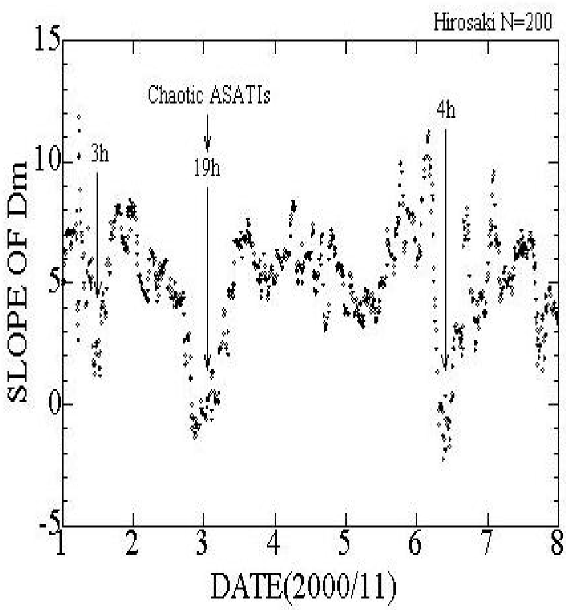

Fig. 4. The time variation of the *Slope* of the D_m-curve of ASATIs observed at Hirosaki array in Nov.2000.

rays is assumed to arrive at the earth usually but they have too much noise from the fluctuation of Galactic magnetic field at most cases. Besides, the time variation of the $Slope$ sometimes has another trough around the right ascension 11 hour, though the constancy less tha 5 of D_m-value of 300 ASATIs is rarely obtained since the mixture of the noise around the direction 11 hour.

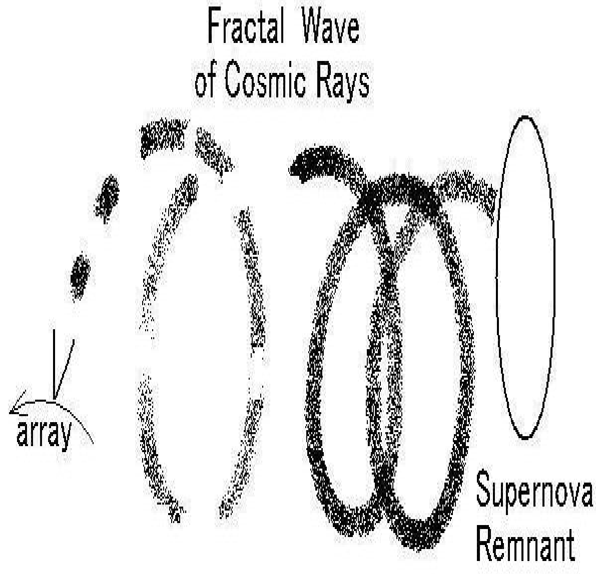

Fig. 5. The fractal wave model of the chaotic cosmic rays.

3 Discussion

The frequency distribution of the right ascensions of the chaotic ASATIs, which has two broad peaks around 4 and 20 hour as shown in Figure 2, indicates that the chaotic cosmic rays come from the specific direction, parallel to Galactic plane. At present observation and analysis, the chaotic cosmic rays should be detected by the air shower array continuously for at least several hours in spite of that the array is moving with the rotation of the earth. Then, the chaotic cosmic rays are supposed to have a fractal wave structure, not a narrow beam, though the zenith angle of the arrival direction is less than 50 degree.

The origin of chaotic feature should not be too far or too old, since cosmic rays are supposed to be randomized after traveling long distance in Glactic magnetic arms. Where and how the long string of fractal cosmic ray wave structure is formed? We may assume a accelerator like a shock fronts on a supernova remnant(A.R.Bell et al.,2001), Cygnus X-3 as a candidate, who may be able to trap the itinerant cosmic rays and accelerate them until they satisfy a condition and release them forming the fractal wave structure toward the direction parallel to the Galactic plane as shown in Figure 5.

This scenario is similar to the chaotic dynamics of the dripping tap (R.Show et al.,1989) especially in that the initial data are the time-series of the arriving intervals. The Larmor radius is about 0.1pc for the cosmic ray particle with the energy 3×10^{14}eV. The short duration of the chaotic ASATIs (nealy 10 hours) and the low frequency of it (several times per year at a station) may be caused by the fluctuation of the long range fractal structure with repeated Larmor rotations. Now, it is necessary to study the non-linear accelerlation dynamics by the shock fronts on a supernova remnant to generate the fractal wave structure of the cosmic rays.

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References

T.Kitamura,S.Ohara,T.Konishi,K.Tsuji,M.Chikawa,W.Unno, I.Masaki,K.Urata and Y.Kato., Astro Particle Physics, **6**, 279 (1997).

W.Unno,S.Ohara,K.Urata,I.Masaki,T.Kitamura,T.Konishi, K.Tsuji,M.Chikawa and Y.Kato., Europhysics Letters, **39**, 465 (1997).

S.Ohara,T.Konishi,K.Tsuji,M.Chikawa,Y.Kato,T.Kitamura, W.Unno,N.Ochi,T.Wada,I.Yamamoto,N.Takahashi and LAAS Group.,Submitting to Nuovo Cimento.

T.Konishi,M.Chikawa,Y.Kato,N.Ochi,S.Ohara,N.Takahashi, K.Tsuji,T.Wada,I.Yamamoto, and LAAS Group., IL Nuovo Cimento to be published.

P.Grassberger and I.Procaccia., Phys. Rev. Letts.,**50**, 346 (1983).

J.Theiler,Phys.Lett.A,**55**, 480(1991).

A.R.Bell and S.G.Lucek.,Monthly Notices of the Royal Astronomical Society,**321**, 433 (2001).

R.Show et.al.,Scientific American,December(1989).