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学位論文題目　High Spatial Resolution imaging for the Nobeyama Radioheliograph and Observations of Weak Activities Prior to Solar Flares

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論文内容の要旨

High Spatial Resolution Imaging for the Nobeyama Radioheliograph and Observations of Weak Activities Prior to Solar Flares

The aim of this paper is two-fold. Firstly, we present 'High Spatial Resolution Imaging for the Nobeyama Radioheliograph' which enable us to synthesize partial frame images of the Sun with a spatial resolution of 10 arcsec at 17 GHz, and secondly, results of 'Observations of Weak Activities Prior to Solar Flares' which have been obtained by using this new imaging software.

Solar flares are processes in which a large amount of magnetic energy is slowly built up in the solar corona and explosively released. Knowledge of coronal conditions prior to solar flares is essential to understanding how energy is stored and then released in solar flares. In order to study the pre-flare coronal conditions, we have analyzed in detail weak activities prior to flares for 32 events which were observed with the Nobeyama Radioheliograph. The Radioheliograph is a quite suitable instrument for statistical analysis of transient phenomena such as solar flares, since it can observe activities anywhere on the Sun, with spatial and temporal resolutions of 10 arcsec and 1 sec respectively, during 8 hours every day.

The Nobeyama Radioheliograph is a radio interferometer dedicated to solar observations. The array configuration of the Nobeyama Radioheliograph is specially designed only for solar observations and so very unique as compared with other radio interferometers for solar and non-solar observations. An imaging software with both high spatial resolution and high image quality is required in order to analyze weak activities prior to solar flares, though it is quite difficult to realize such an imaging software by usual imaging techniques in our unique array. We have succeeded to develop a new imaging software in which two requirements, i.e. high spatial resolution and high image quality, are fulfilled.

(1)High Spatial Resolution Imaging for the Nobeyama Radioheliograph

The Nobeyama Radioheliograph is a multiple, equally spaced T-array which consists of eighty-four 80-cm antennas arranged in the T-shaped baseline with 490 m in the east-west and 220 m in the north-south directions. Phase and gain errors mostly caused by atmospheric fluctuations can be calibrated by making use of redundancy of the antenna configuration, using the Sun itself as a calibrator. The absolute position of the synthesized image of the Sun can not be obtained in this self-calibration method, and therefore, is determined relative to the solar disk using the sharp limb of the high-quality image of the solar disk. In order to get the high-quality image of the solar disk, complex visibility measured by the Radioheliograph is heavily weighted on lower spatial frequencies. In the Nobeyama Radioheliograph, the spatial resolution of 10 arcsec can be expected at 17 GHz from the maximum antenna spacing. However, if the image is synthesized using the natural weighting, the synthesized main beam has extended wings around the sharp beam, and as

a result, the spatial resolution of the synthesized image is very poor, almost double that expected from the maximum antenna spacing. In order to achieve the instrumental limit in spatial resolution, it is necessary to weight the sampled visibility so that the contribution from any part of visibility space is uniform (this is called the super uniform weighting). In this case, the synthesized beam (the point spread function) has extremely high sidelobes (about 90 % of the main beam level). This causes high probability of generation of spurious sources in case of imaging of the full Sun, since many radio sources are scattered on the solar disk.

We develop a new algorithm for a localized field of view on the Sun in order to overcome the above mentioned problem. The principle of the new algorithm is as follows. We consider the case that the radio sources to be synthesized are confined in the target region which is smaller than the interval of the high sidelobes. If we can separate visibility of radio sources in the target region from that outside the target region, the super uniform weighting can be safely applied to imaging of the target region (whose visibility is separated from that outside the target region) because no serious interaction between the high sidelobes and the radio sources can be expected in the target region. Then, we find that the natural weighting can be used to separate visibility of the radio sources between the inside and the outside of the target region because the synthesized beam (the point spread function) has lower sidelobes and many full disk maps have been successfully synthesized using the natural weighting. One of the weak points of the CLEAN algorithm is avoided in the newly developed software, and as a result, the instrumental limit of spatial resolution, $\sim$ 10 arcsecond, is achieved in the Nobeyama Radioheliograph at 17 GHz. This algorithm makes it possible to synthesize high spatial resolution maps not only of flares but also of relatively bright active regions.

The noise level on the map synthesized by the new algorithm is about 1300 K in the quiet time (RMS) corresponding to the noise level of system temperature so that the structure greater than $5\sigma \sim 6500$ K is detectable for the map with 10 arcsecond of the spatial resolution. During a flare, on the other hand, the dynamic range defined as the ratio of the peak brightness to the maximum error sidelobe level is $\sim$ 400 (26dB) for the peak brightness temperature larger than 2×10^6 K.

A similar algorithm is used to restore a weak source located near an intense point-like source such as quasars to reduce the computing time in non-solar observations. However, it is the first time that this algorithm is applied to achieve the high spatial resolution.

(2) Observations of Weak Activities Prior to Solar Flares

We study weak activities prior to solar flares using data from the Nobeyama Radioheliograph at 17 GHz at the beginning of routine observations (late June, 1992) and December 31, 1993. 32 events accompanied by GOES M-class flares are selected. The radio images used in this study are synthesized using the newly-developed imaging software described in the previous section. This software is necessary to reveal fine structures in both pre-flare and main-flare phases. The main results from this study are as follows.

(1) The statistical analysis of occurrence of pre-flare activities in main flare sources shows that all of the events are accompanied by significant pre-flare activities with excess brightness temperature ranging from 3×10^3 K to 10^5 K.

(2) A typical pre-flare structure of long-duration events is found by analyses of limb events. Weak pre-flare activities are extended in a wide region surrounding the main flare source. The structure with the largest intensity increase in the pre-flare phase can be seen above the main flare source and extends in the radial direction from the main flare source to the higher level in the corona. This elongated intensity increase is accompanied by significant intensity decrease in the corona surrounding the main flare source. Combination of the intensity increase and decrease seems to be already created about 2 hours prior to the onset of the main flare.

(3) Observations of the disk events show that the majority of the disk events have complex source structures, which consist of two or more loops, in the main phase. Pre-flare activities can be found in all of the main flare loops for all of the events with complex source structures. This is also true for the special events, which have a "two loops with three legs" structure, recently presented by Nishio et al. (1997) and Hanaoka (1997) based upon simultaneous microwave and X-ray observations. In such events, pre-flare activities can also be seen in both of the main flare loops.

論文の審査結果の要旨

本論文は、１９９２年に国立天文台野辺山太陽電波観測所に建設された、太陽観測専用の電波干渉計（電波ヘリオグラフ）の高分解能像合成アルゴリズムの開発と、それを活かした太陽フレアの前兆現象の研究について述べたものである。

電波のヘリオグラフは直径８０cmのアンテナ８４台を東西４９０m、南北２２０mの基線上に配列した電波干渉計で、観測周波数は１７GHzである。（１９９６年より３４GHzでも観測を行なっているが、本論文では１７GHzのデータのみ扱っている。）観測から直接得られるのは、様々な基線長のアンテナ対からの出力（フーリエ成分）であり、観測対象の像を得るには、CLEANなどと呼ばれる像合成計算を行なう必要がある。これまで電波ヘリオグラフの像合成に標準的に使われてきたアルゴリズムでは、太陽全体にわたって質のよい画像を得ることに主眼を置き、基線長の短いフーリエ成分のウェイトが高い像合成法を採ってきたために、実効分解能は２０秒角程度で、アンテナの最大スパンに対応する、１０秒角の分解能は得られていなかった。本論文では、基線長の長いフーリエ成分も同じウェイトで取り入れ、このために生じるアンテナビームのにせのピークは像合成の視野を得ることで除去する新しいアルゴリズムを考案し、限られた視野（５分角、太陽の直径は３０分角）の中では１０秒角の分解能を達成できることを示した。この手法は現在では電波ヘリオグラフの標準合成法の一つとなっており、他の研究者によっても活用されている。

以上の研究で電波強度の弱い場合にも高分解能の画像が得られるようになったことを活かして、次にフレアの前兆現象の研究を行なった。これまで、太陽のフレア爆発の数十分前に、弱い活動現象がフレアの前兆として観測されることが報告されていた。太陽からのX線や電波の総放射を観測する装置では、このような前兆が見つかるのはフレアの２～３割とされていた。本論文では、比較的大規模のフレア３２例について解析し、そのすべてについて何らかの前兆現象が見いだされた。これは電波ヘリオグラフの感度が高いことと、高分解能の２次元画像が得られていることによると解釈される。また、フレアの前兆時に、フレアの主たる電波源近くに電波強度が増光する領域がある一方、その周りには電波増光とほぼ同期して徐々に電波強度が下がっていく領域があることがわかった。これはこれまでに知られていなかった現象で、一つの解釈として、フレアのエネルギー解放を担う磁気リコネクション過程がフレア前にも徐々に進行しており、リコネクション領域へ向かってプラズマが流れ込むために周辺領域の密度が下がるということが考えられる。X線の同時観測データのそろっている例が少なく、解析例すべてについて物理量を決めることができなかったのは残念であるが、太陽フレアのメカニズムの研究に大きな貢献となったことは間違いない。

本審査委員会は、以上の研究内容と成果は博士学位論文として十分の内容を備えたものであると判断した。