OBSERVATIONAL EVIDENCE OF A SOLITON LIKE FEATURE IN THE ACTIVE REGION NOAA 8214 AND ITS MODELING USING THE NONLINEAR SCHRÖDINGER EQUATION

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НАБЛЮДАТЕЛЬНОЕ СВЕДЕНИЕ О СОЛИТОНОПОДОБНОМ ОБРАЗОВАНИИ В АКТИВНОЙ ОБЛАСТИ NOAA 8214 И ЕГО МОДЕЛИРОВАНИЕ С ПОМОЩЬЮ НЕЛИНЕЙНОГО УРАВНЕНИЯ ШРЕДИНГЕРА

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Мы анализируем событие TRACE, которое произошло 9 мая 1998 года в 13:09 UT и продолжалось до 13:13 UT в активной области NOAA 8214. Событие представляет собой вспышку класса C 6.6 по данным космических обсерваторий YOHKOH и GOES. Это событие, которое длилось около 4 минут, показывает распространяющийся солитон в конечной фазе вспышки. Скорость солитона составляет около 1764 км/с, что соответствует скорости быстрой магнитозвуковой моды. Ранее нелинейная радиальная мода в корональных петлях моделировалась с использованием нелинейного уравнения Шредингера (НУШ), приведенного в [3, 4], и мы используем это уравнение для получения необходимых нелинейных параметров для определения магнитного поля в месте события.

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We present one of the most visible and obvious evidence of a soliton like formation during the C 6.6 class solar flare that occurred on 1998-05-09 from 13:09:33 UT till 13:13:53 UT in the active region NOAA 8214. This flare was photographed with the space based solar observatory TRACE, that was launched on the 2nd of April 1998. The interesting aspect of this flare is that it has a circular flaring ring around the main flaring site. The ring showed an impulsive event followed by a soliton like feature that ran across the semi circumference of the ring as shown in the figures 1 and 2. From these figures we can see that the original perturbation tends to settle into a soliton like feature. As we can see excellent modulation of the intensity by this soliton like feature, we can say that it is predominantly a sausage mode.

The semi circumference of the circular flaring ring is calculated to be $L \approx 104958$ km. The time step between successive photographs made by TRACE

in this case is calculated to be $\Delta t = 3.24s$ by accounting for the time taken by the flare and the total number of photographs taken from the beginning till the end. By considering the semi circumference and the number of time steps between the beginning and the end of the perturbation event, the average velocity of the perturbation is obtained to be approximately 1764 km/s. As the soliton like feature travels all along the semi circumference, we can introduce a magnetic tube configuration along the circumference, which serves as a wave guide for the perturbation. The radius a of this tube is calculated from the photographs to be around $a \approx 936.57 \text{ km}$ and as $\frac{a}{L} \ll 1$, we can use the homogenous infinitely long flux tube model. This fact along with the fact that the perturbation is predominantly a fast sausage mode lets us use the nonlinear Schrödinger equation derived in [3, 4] which is given by the following expression:

$$i \left(\frac{\partial \psi}{\partial t} + V_g \frac{\partial \psi}{\partial z} \right) + \alpha \frac{\partial^2 \psi}{\partial z^2} + \sigma |\psi|^2 \psi = 0 \quad (1)$$

Here ψ , V_g are the radial velocity amplitude and group velocity of the fast sausage mode respectively and α , σ are the nonlinear coefficients. Such a nonlinear Schrödinger equation (NLS) describes a quasi-monochromatic wave in terms of four wave scattering in the envelop approximation [2]. The velocity amplitude A of the perturbation while it approaches soliton like state is estimated to be $A \approx 588 \text{ km/s}$. In order to evaluate the model nonlinear parameters α and σ for this case we introduce full width at 95% maximum given by $F_{95\%} = \frac{1}{A} \sqrt{\frac{2\alpha}{\sigma}} \ln(2)$. The average value of this parameter is calculated from the photographs by determining the distance between the ends at which the intensity in terms of pixel units falls to 95% of the maximum.

In [3,4], α , σ and V_g were calculated for three different cases i.e. $V_e = 3V_i$, $V_e = 6V_i$ and $V_e = 9V_i$, where V_e, V_i are the external and internal Alfvén velocities respectively. As the tube under investigation corresponds to a flaring loop, we can consider the case of $V_e = 9V_i$ in which case we have ratio of internal to external equilibrium densities with respect to the introduced flux tube as $\frac{\rho_0}{\rho_e} = 81$. The graphical dependance of V_g , α and σ in terms of dimensionless variables is shown in the figures 3 and 4 respectively. As these coefficients are calculated in terms of the normalized system of units i.e., they are calculated by considering $V_i = 1$, $\rho_e = 1$, $a = 1$ we must calibrate the velocity amplitude in terms of the internal Alfvén velocity V_i to estimate the nonlinear parameters of the NLS equation given by (1). As we don't know the actual internal Alfvén velocity V_i yet, we use the observed group velocity of the soliton like feature as the first order approximation for the V_i and normalize the velocity amplitude A by dividing it with this velocity. The obtained normalized A is then used along with $F_{95\%}$ to obtain the first order approximation of the ratio $\frac{\alpha}{\sigma}$. Now from the figures 3 and 4, we choose α and σ such that their ratio is as close as possible to the first order approximation ratio obtained previously and take the normalized

Fig. 1. TRACE photograph on 1998-05-09 showing the active region NOAA 8214 at Time 13:15:43 UT. The soliton like feature a little after the beginning phase is marked with a white circle.

Fig. 2. TRACE photograph on 1998-05-09 showing the active region NOAA 8214 at Time 13:16:22 UT. The soliton like feature at the end phase is marked with a white circle.

Fig. 3: The bottom and top curves show the dependences of dimensionless nonlinear parameters α and V_g with respect to the dimensionless wavenumber ka of the central carrier wave.

Fig. 4: The curve shows the dependance of dimensionless nonlinear parameter σ with respect to the dimensionless wavenumber ka of the central carrier wave.

group velocity V_g corresponding to these nonlinear parameters. The newly obtained normalized V_g along with the observed group velocity of the soliton like feature are used in the second order iteration. This iteration process can be repeated several times to get better accuracy. The process is convergent like

because the group velocity has no singularities in the anomalous dispersion region and approaches the internal Alfvén velocity.

In this way we have obtained two sets of appropriate values of α and σ given by $(\alpha, \sigma) \approx (0.02299, 0.02546)$ and $(\alpha, \sigma) \approx (0.06254, 0.04091)$ with the respective values of normalized v_g as 0.8286 and 0.6762 respectively.

The magnetic field can be estimated from the internal Alfvén velocity as follows: The two possible values of the Alfvén velocity obtained after determining the accurate normalized group velocity are 2129 km/s and 2609 km/s. The order of the particle number density can be crudely estimated by considering the fact that for larger densities i.e. $\sim 10^{12}/\text{cm}^3 - 10^{13}/\text{cm}^3$, radiative cooling acts as the dominant mechanism for cooling. The scale of time for radiative cooling for densities ranging from $\sim 10^{11}/\text{cm}^3$ to $\sim 10^{12}/\text{cm}^3$ at temperatures $\sim 2\text{MK}$ is around $\sim 130\text{s} - 13\text{s}$ [1] and the time taken for the circular ring to fall to the background intensity level from the beginning of the soliton like event is obtained to be around $\sim 35\text{s}$. This suggests that the density of the region corresponding to the circular ring is around $\sim 10^{11}/\text{cm}^3 - 10^{12}/\text{cm}^3$. By taking the average of these extreme values and also considering the fact that in the Corona, the particle density ratio of Hydrogen to Helium is around 10:1, we obtain 778 G or 953 G as the two possible estimates for the magnetic field at the site of the perturbation. This suggests a new approach to evaluate magnetic fields by using nonlinear phenomena like solitons as the diagnostic tools and therefore can be treated as a method of **nonlinear coronal seismology**.

Nonlinear coronal seismology has a great potential in the future when space borne telescopes with very high resolutions of the order of $\leq 0.1''$ will be available.

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