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Magnetohydrodynamic Explosive Phenomena in the Solar and Astrophysical Plasmas
太陽・天体における電磁流体爆発現象

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Modern view of explosive phenomena in the universe such as flares and jets in active galactic nuclei and young stellar object is reviewed with an emphasis of possibility of magnetohydrodynamic (MHD) interpretation based on solar flare MHD model. The unified reconnection model for solar flares has been proposed and applied to stellar flares and magnetar flares. Finally, we discuss recent discovery of many superflares on solar type stars.

1. Introduction

Recent astronomical observations have revealed that our universe is full of explosions. The biggest explosions after the Big Bang of our universe itself are the explosion of nuclei of galaxies, called AGN (active galactic nuclei). AGN releases huge energy (~ 10^{62} erg in 10^{8} years) through all electromagnetic spectrum with high time variability (called flares or bursts), and produce well collimated relativistic jets. AGN probably contain supermassive black holes at their center, but their true properties are still very puzzling.

The miniature versions of AGN have been discovered in various objects, such as close binary systems and young stellar objects. These phenomena also show many flares/bursts as well as jets or mass ejections. Although the progress of observations and theoretical understanding of these objects is rapid, the basic mechanism of formation of jets and flares has not been well understood.

The nearest example of miniature of AGN is the explosion in the solar atmosphere, called solar flares. The typical solar flare releases total energy of 10^{29}~10^{32} erg and expels large amount of mass ~10^{15} g into interplanetary space in the largest event. When such mass (called coronal mass ejections or CMEs) with southward magnetic field hits the Earth, geomagnetic storm occurs, eventually leading to aurora-substorm near the north and south poles.

As for the origin of solar flares, it has been established in mid-twenty centuries that the source of energy of solar flares is the magnetic energy stored near sunspots. After that, various magnetohydrodynamic (MHD) mechanism has been proposed to explain solar flares. Hence many astrophysicists applied MHD models of solar flares to various cosmic jets and flares, including AGN jets. One such example is the MHD model of astrophysical jets proposed by Uchida and Shibata [1,2].

It has also been found that many normal stars show flares which are very similar to solar flares. Of course, the three dimensional structure of these stellar flares have never been observed, so their origin have not yet been solved. However, there are increasing evidence that these stellar flares are quite similar to solar flares, so that it has been believed that MHD mechanism is the promising mechanism for the origin of stellar flares.

Hereafter, we will discuss the present status of understanding of the origin of solar flares, and then discuss application of solar flare model to stellar flares. We also discuss newly discovered superflares on solar type stars. Finally, we will discuss application of solar flare model to giant flares in magnetars.

2. Solar Flares

A solar flare was first discovered by Carrington in 1859 during visual observations of sunspot. Since then, its mechanism has been puzzling. However, Japanese solar satellite, Yohkoh, revealed various evidence of magnetic reconnection in soft X-ray observations in 1992-1995 [3,4,5] and established at least phenomenologically that the solar flare is caused by magnetic reconnection mechanism [6].

Figure 1 shows the unified model of solar flares which are developed on the basis of Yohkoh soft X-ray observations and MHD theories of reconnection [6,7, 8]. It should be noted here that there is a huge scale gap between microscopic plasma scale such as ion Larmor radius or ion skin depth (~ 10 cm) and flare size scale (~ 10^{9} cm).

Hence the basic mechanism of fast reconnection suitable for solar flares (and cosmic flares as well) cannot be solved from microscopic plasma physics alone. Instead, we have to consider the effective way to connect micro and macro scales to explain fast reconnection in solar and cosmic flares, which may be realized by plasmoid-induced reconnection and fractal reconnection [8, 9].

3. Stellar Flares

Shibata and Yokoyama (1999, 2002) noted that there is a remarkable empirical correlation between emission measure and temperature of solar flares, solar microflares, stellar flares and young stars' flares. Then they successfully explained the correlation using the magnetic reconnection theory developed by Yokoyama and Shibata (1998). This means that this correlation can be indirect evidence of magnetic reconnection in stellar flares.

Recently, Maehara et al. (2011) [13] discovered in Kepler satellite data that there are many superflares (with energy 10^{34}~10^{35} erg, which is 100~1000 times that of the largest solar flare observed so far) on solar type stars whose rotational velocity is similar to that of the Sun. This is a surprising result because this suggest that such superflares may occur on our present Sun and if so they will damage our civilization heavily. Why and how such superflares occur on our Sun at present will be an urgent issue from space weather point of view.

4. Magnetar Flares

Magnetars are neutron stars with super strong magnetic field ~ 10^{15} G, and sometimes produce giant flares. Masada et al. (2010) [14] applied solar flare model to such giant flares in magnetars. It has been thought that the huge amount of magnetic energy are stored in the interior of magnetars. Sometimes, such magnetic energy has been released by fast reconnection mechanism occurring in the magnetosphere of magnetars. One interesting future subject to be studied in detail is the coupling between magnetic reconnection and QED effect.

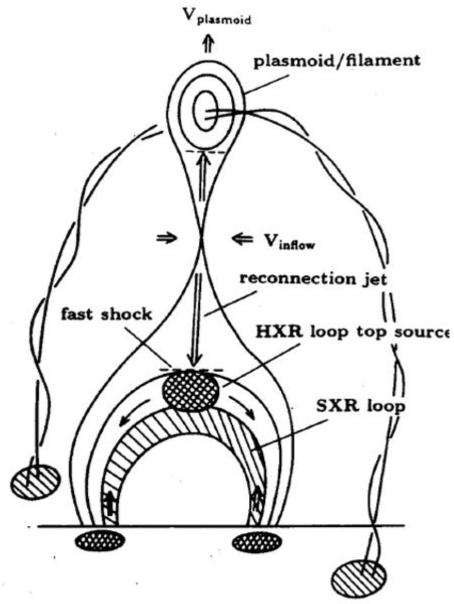

Fig.1. Unified reconnection model of solar flares [6]

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