博 士 (理 学) フィニー オクタリアニ

学 位 論 文 題 名

A Study of Global Oscillations in Gaseous Disks

(ガス円盤中の大域振動の研究)

学位論文内容の要旨

Oscillations are ubiquitous phenomena found in gaseous disks such as circumstellar disks or accretion disks. These oscillations usually cause variability in the spectra of the object. The study of disk oscillation is important to give deeper understanding of the physics of these disks. In this thesis, as the origins of long-term variability in circumstellar disk around B emission stars (hereafter, Be stars) and quasi-periodic X-ray variability in black-hole accretion disks, we investigate the following two types of disk oscillations.

(1) Global one-armed oscillations in circumstellar disks of Be stars

Spectrum of a star usually shows only absorption lines, but there are several types of stars that also show emission lines in their spectra. One of these types of stars is called B emission stars (or Be stars, for short). Be stars are non-supergiant B-type stars whose spectra show one or more hydrogen Balmer lines in emission. Be stars have a cool equatorial disk (hereafter, Be disk) around the central star. The Be disk is a geometrically thin, high-density region with material rotating at nearly Keplerian velocity. The emission lines of Be stars arise from the Be disk.

The most plausible model for the Be disk is the viscous decretion disk model (Lee et al. 1991). In this model, when the star ejects mass from an equatorial surface, a decretion disk forms, where the material drifts outward, not inward, by the effect of viscosity. Although the viscous decretion disk model explains many observed features of Be stars, there are many open questions on the structure, evolution, and variability of Be disks. Studying them forms the major part of the Be star research.

Decretion disks share many characteristics with accretion disks, except for the direction of mass flow in the disk. Kato (1983) showed that in a nearly Keplerian accretion disk, a one-armed global mode (hereafter, a one-armed oscillation) shows up as a very slowly revolving perturbation pattern. In Be decretion disks, there are also one-armed oscillations, whose precession causes long-term variability in emission line profiles. The observed (quasi-)period of line profile variability ranges from 5 to 10 years for isolated Be stars, and 1 to 3 years for Be stars in binary systems.

Previous theoretical studies of global one-armed oscillations in Be disks are limited to the case for isolated Be stars. Moreover, most of those studies assumed that the Be disk is steady and has a power-law density distribution, for simplicity. However, many Be stars are found in binary systems, where the presence of the companion is most likely to affect the disks and the global mode oscillation in the disk. For example, Be disks in binary systems are known to be smaller because they are truncated by the tidal torques of the companion star. In addition to this, some Be stars exhibit observational evidence of dissipation and re-formation of the equatorial disk, during which the density distribution in the disk are likely to be different (and sometimes far) from the usually assumed, power-law form. For example, in the disk dissipation stage, there is an observational evidence that the innermost part of the disk is cleared, opening a gap between the star and the inner edge of the disk. It is thus important to study global one-armed oscillations with a more realistic disk model, taking into account the above observational features. Therefore, we study the global one-armed modes in:

- disks around binary Be stars, where the effects of the tidal interaction with the companion are taken into account, and
- evolving disks.

In these studies, we take account of the three-dimensional oscillation structure, which was found by Ogilvie (2008) to improve the mode confinement in the disk.

In the former study, we find that the period of the linear, global one-armed modes is shorter and the modes are better confined in closer binary systems, where the effect of the companion to the Be disk is stronger than in wider systems. This trend is also seen in systems where the binary mass ratio (ratio of the mass of the companion star and the Be star mass) is higher. The eigenmode is insensitive to the spectral type of the central star.

In the latter study, we first calculate the density evolution in the disk formation/dissipation stage, using a one-dimensional isothermal disk model with the viscosity parameter $\alpha = 0.1$. Then, we seek linear one-armed eigenmodes for the obtained density distribution at several epochs. In the calculation for the disk formation stage, we inject mass at a constant rate at a radius just outside the star. We run the calculation for this stage for ten years, but the disk is already fully developed several years after the disk formation begins. As the disk grows, the density distribution approaches the power-law distribution corresponding to the steady disk state, particularly in the inner part. The frequency of the one-armed mode also increases toward the frequency found for the steady disk. Next, in order to model the disk in the dissipation stage, we turn off the mass injection and calculate the density evolution for another ten years. As in the disk formation stage, we seek linear one-armed eigenmodes for the obtained density distribution at several epochs. Getting no mass supply from the star, the accretion starts from the innermost part of the disk. As time goes on, the accreting region becomes wider. As expected, the density distribution of the disk in the accretion region is far from a power-law form. We also find that in the disk dissipation stage, the fundamental one-armed mode has significantly higher frequency and smaller propagation region than in the disk formation stage.

These results show that it is important to take into account the tidal effect if the Be star is in binary and a realistic density distribution if the disk is forming/dissipating.

(2) Resonant excitation of trapped g-mode oscillations in black-hole accretion disks

X-ray satellites have detected high-frequency quasi-periodic oscillations (hereafter, HF QPOs) in black-hole X-ray binaries. HF QPOs occurs at fixed frequencies (≥ 100 Hz), and they appear only in high-luminosity states where $L > 0.1L_E$, with L_E being the Eddington luminosity. The high frequencies of HF QPOs suggest that they are the phenomena originating in a strong gravitational field near the black hole. HF QPOs can be a powerful tool to explore the mass and spin of the central black hole. Understanding HF QPO is important, given there is still no reliable means to measure these black-hole parameters.

Our study is based on the model proposed by Kato (2004), where HF QPOs are regarded to be trapped disk oscillations resonantly excited in deformed disks. The deformation of the disk could be a warp or an eccentric deformation. An outline of Kato's model is as follows: A non-linear coupling between a trapped oscillation (hereafter, an original oscillation) and a deformed part of the disk causes forced disk oscillations (hereafter, intermediate oscillations). The intermediate oscillation makes a resonant coupling with the disk, and provides a positive feedback to the original oscillation. As a result, the original oscillation is amplified. We numerically study this model based on the recent formulation by Kato (2008).

We first obtain trapped g-mode oscillations with eigenfrequencies close to the maximum of the horizontal epicyclic frequency. Then, we examine whether these modes are excited via the resonant coupling with the warp of the disk. We find that the fundamental modes of the trapped g-mode oscillations in a warped disk are excited by this mechanism, except in the case of non-rotating black holes. Studying the effect of the black-hole and accretion-disk properties on these trapped oscillations, we find that the growth rate increases as the warp amplitude or the black hole spin parameter increases, whereas it decreases as the sound speed increases.

学位論文審査の要旨

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学位論文題名

A Study of Global Oscillations in Gaseous Disks

（ガス円盤中の大域振動の研究）

星周円盤（星の周囲に形成されるガス円盤）や降着円盤のようなガス円盤を持つ天体では、ガス円盤に起因する活動性が見られる。一般に、これらの天体の活動性は光度やスペクトルの変動を伴い、そのような変動の多くがガス円盤の成長・減衰や振動に起因するものであると考えられている。しかし、天体の種類によっては、振動の構造や性質については未解明な部分も多く、そのような分野では観測と比較ができるレベルの信頼できるモデルの構築が求められている。

本論文において申請者は、主に、Be星（星周円盤を持つ星で、スペクトル型がB型。B型輝線星とも言う。eはemissionを表す）のガス円盤中の大域振動の研究を行った。この分野における従来の研究は、簡単化のために、定常円盤であること、および単独星であることという2つの仮定をおいていたが、申請者はより一般的に、成長・減衰するガス円盤の構造を計算し、進化する円盤中での大域振動を単独星の場合だけでなく連星系の場合についても求めた。

その結果、成長中のガス円盤中の大域振動は振動数が定常状態のものと比べて低いこと、また成長とともにその振動数は定常状態のものに漸近すること、さらに減衰中の円盤では、中心星と円盤の間にギャップ（低密度領域）が生じ、その効果により振動の振動数が高く、伝播範囲が狭くなるなどの結果を得た。

これを要するに、著者はBe星の星周円盤の成長・減衰の効果および連星系における伴星の重力の効果が振動に及ぼす影響を初めて明らかにしたものであり、当該分野の研究に対して貢献するところ大なるものである。よって著者は、北海道大学博士 (理学) の学位を授与される資格があるものと認める。