学校编码：10384　　　　分类号______密级______
学号：19820130154231　　　　UDC______

厦门大学

博　士　学　位　论　文

X 射线双星多波段辐射及磁流体力学湍流的研究

Studies on Multiwavelength Radiation of X-ray Binaries and Magnetohydrodynamic Turbulence

张建福

指导教师姓名：　卢炬甫　教授

专　业　名　称：　理　论　物　理
论文提交日期：　2016 年 3 月
论文答辩时间：　2016 年 4 月
学位授予日期：　2016 年　　月

答辩委员会主席：__________
评　　阅　　人：__________

2016 年 4 月

厦门大学学位论文原创性声明

本人呈交的学位论文是本人在导师指导下，独立完成的研究成果。本人在论文写作中参考其他个人或集体已经发表的研究成果，均在文中以适当方式明确标明，并符合法律规范和《厦门大学研究生学术活动规范（试行）》。

另外，该学位论文为（　　　　　　　　　　　　）课题（组）的研究成果，获得（　　　　　　　　　）课题（组）经费或实验室的资助，在（　　　　　　　　　）实验室完成。（请在以上括号内填写课题或课题组负责人或实验室名称，未有此项声明内容的，可以不作特别声明。）

声明人（签名）：

年　月　日

厦门大学学位论文著作权使用声明

本人同意厦门大学根据《中华人民共和国学位条例暂行实施办法》等规定保留和使用此学位论文，并向主管部门或其指定机构送交学位论文（包括纸质版和电子版），允许学位论文进入厦门大学图书馆及其数据库被查阅、借阅。本人同意厦门大学将学位论文加入全国博士、硕士学位论文共建单位数据库进行检索，将学位论文的标题和摘要汇编出版，采用影印、缩印或者其它方式合理复制学位论文。

本学位论文属于：

（　）1.经厦门大学保密委员会审查核定的保密学位论文，于　年　月　日解密，解密后适用上述授权。

（　）2.不保密，适用上述授权。

（请在以上相应括号内打“√”或填上相应内容。保密学位论文应是已经厦门大学保密委员会审定过的学位论文，未经厦门大学保密委员会审定的学位论文均为公开学位论文。此声明栏不填写的，默认为公开学位论文，均适用上述授权。）

声明人（签名）：

年　月　日

摘　要

本学位论文的研究主要致力于两个科学目标，其一是理解 X 射线双星多波段辐射的起源及特性；其二是基于同步辐射偏振色散的统计技术，使用数值模拟方法研究磁流体力学(MHD)湍流的性质。基于强子或轻子主导辐射的假设，论文建立 X 射线双星主要活动区的辐射模型，如喷流底、中部区、喷流终端与周围星际介质(ISM)作用区、吸积盘、磁层等辐射区，研究多波段光子谱及高能中微子的辐射。MHD 湍流是天体内部物质运动的必然结果，研究它有重要意义，因为对它的研究不仅可以促进人们理解 X 射线双星的高能过程，而且它对恒星的形成、宇宙射线的传播及加速、热传导、磁重联等都有重要影响。

基于强子辐射主导的考虑，我们在第二章中分别研究喷流底部区、整个喷流区、喷流终端与 ISM 作用区产生的多波段能谱及潜在的中微子辐射。第一、发展喷流底部区的辐射模型是为了预测小质量微类星体中潜在中微子辐射，通过 GX 339–4 低能波段现有观测及 Fermi LAT、HESS、CTA 的灵敏限的限制，我们获得潜在的中微子发射事件数，结果表明小质量微类星体是可能的中微子发射源，立方千米尺度的中微子望远镜有能力探测到它们的发射信号，能对我们的模型进行检验。第二、提出整个喷流尺度区的模型是为了理解大质量微类星体的多波段辐射起源，辐射、吸收导致的轨道调制特性，该模型能近似解释 LS I +61° 303 上、下合位置附近的多波段观测。第三、建立喷流终端与 ISM 作用的辐射模型是受到 Cygnus X–1 的观测的激发，我们想要知道这个区是否存在高能及甚高能辐射信号，建设中的 CTA 能否有机会探测到可能的辐射信号。通过构建喷流与 ISM 作用的双激波辐射模型，我们发现结论是乐观的，并预言微类星体族的辐射可能贡献部分银河宇宙射线。

在第三章轻子模型的研究中，通过类比研究河外耀变体的方法，我们发展适合于大质量 X 射线双星喷流的二维(2D)辐射模型，提出小质量微类星体喷流中的伽玛射线辐射模型。通过求解电子的演化方程，研究各种冷却机制在不同喷流位置处扮演的角色，详细追踪相对论电子沿喷流方向的演化过程，同时模拟各喷流位置处的辐射能谱分布，叠加这些能谱得到总输出谱。模型应用到黑洞 X 射线双星 Cygnus X–1 的结果表明：(1) Cygnus X–1 的射电辐射起源于从双星系统尺度一直延展到喷流的终端区域；(2) GeV 波段的辐射起源于靠近双星系统尺度区；(3) TeV 波段的辐射起源于双星系统尺度之内，本文预言这些辐射有机会被 CTA 探测到；(4) MeV 尾端辐射信号来自于双星系统尺度之内，而且辐射位置较靠近喷流的底部区域。

在 2D 轻子模型的框架下，通过注入分段幂律电子谱，我们研究了 Cygnus X–3 高软态期间的多波段辐射。我们强调 Cygnus X–3 是态转变的特列，它违反传统的 X 射线双星态转变模式，即在其高软态活动期间仍然存在喷流现象。研

究发现 Cygnus X–3 辐射区不同于传统的持续性的喷流，耗散区仅仅占据较薄的喷流空间区域，导致的辐射信号从非常致密的喷流中部区辐射出来，即约 1 倍轨道距离处。拟合结果能够解释当前的多频观测，能够预测 TeV 波段潜在的伽玛射线辐射；模型可以使用红外波段的偏振观测来检验。除此之外，受到最近中微子观测研究的激发，我们提出小质量微类星体多波段辐射的 2D 轻子发射模型，数值模拟结果表明：纯轻子诱导的多波段能谱成功地延伸到高能及甚高能波段，模型被应用到有较好低能段观测的源 GX 339-4 上，研究表明 Fermi LAT 及 CTA 有能力探测到小质量微类星体的伽玛射线辐射信号，该模型提供了区分 X 射线辐射起源的方法。

在第四章吸积流及磁层辐射模型的研究中，我们详细模拟了喷流辐射盘(JED)的多波段辐射能谱，这个新的模型有自洽处理吸积与喷流耦合的优势，该模型能有前途地解释 X 射线双星的经典谱态。通过数值求解 JED 的动力学平衡方程，获得遵循动力学结构演化的解。热解对应于光学薄、几何厚的径移主导的吸积流(ADAF)；冷解对应光学厚、几何薄的标准盘(SSD)。在分析 JED 动力学结构及多波段辐射谱后，热解谱被成功地应用到 XTE 1118+480 的低硬态观测。此外，论文研究了中子星吸积伴星物质导致的磁层区电场加速粒子的辐射模型，应用该模型到有磁星信号的源 LS I + 61° 303上，我们发现模型能解释 Fermi LAT 观测的截断谱特征，结果认为中子星驱动的吸积系统的高能辐射很可能来自于脉冲星的磁层区。

在第五章磁流体力学湍流的研究中，我们使用合成的数据“立方体”检测新的统计技术，发现数值结果很好地与理论预言吻合。基于 3D、2D、1D 的合成观测，我们发现：(1) 当法拉第旋转测量(RM)为随机磁场主导时，偏振方差[$P^2(\lambda^2)$]服从通常的规律 λ^{-2}；当规则磁场主导 RM 时，偏振方差服从 λ^{-2-2m}。因此，偏振方差反映了垂直于视线方向的磁场分量的统计性质。(2) 偏振对 λ^2 的求导的色散研究显示了一个幂律关系，它应该反映法拉第波动统计，这将激发进一步的理论研究。(3) 相对论电子谱指数的变化不会改变偏振频率分析(PFA)测量的形状，因此也不会阻碍我们获取磁波动的谱性质。(4) PFA 技术已经可以安全地使用来研究银河及河外星系的湍流性质，望远镜角度分辨率和不可避免的噪音的影响不会对恢复潜在的湍流谱造成障碍。

在第六章中，我们总结本论文研究的主要结果，讨论下一步研究工作的方向。第一、我们将开展 X 射线双星中高能粒子如何被加速的研究工作；第二、深入研究 MHD 湍流的性质及它对天体物理过程的影响。

关键词：X 射线双星；微类星体、吸积盘；辐射机制；磁流体力学湍流

Abstract

The research of this dissertation is mainly devoted to two scientific goals. First is to understand the origin and characteristics of multi-frequency emission of X-ray binaries. Second is to study the properties of magnetohydrodynamic (MHD) turbulence by numerical simulations, on the basis of statistical techniques of synchrotron polarization dispersion. Based on an assumption of hadronic or leptonic origin, we propose radiative models located at the main active region of an X-ray binary, such as the base or middle region of jets, the region of jet termination interacting with surrounding ISM, the accretion disk and magnetoshperic regions, in order to study multi-wavelength photon spectra and high-energy neutrino emissions. MHD turbulence is an inevitable result of matter motions in astrophysics. It is important to study MHD turbulence because it not only can promote us to understand high-energy processes of X-ray binaries, but also influence on star formation, transportation and acceleration of cosmic rays, heat conduction, and magnetic reconnection and so on.

On the basis of an assumption of hadronic-dominated emissions, we in Chapter 2 study multi-wavelength photon spectra and high-energy neutrino emissions from different regions of jets. First, to predict potential neutrino emissions from low-mass microquasars, we develop a model located at the base of jets. By the constraints of both the current observations at low-energy waveband and the sensitivity limits of telescopes from Fermi Large Area Telescope (LAT), High Energy Stereoscopic System (HESS) and Cherenkov Telescope Array (CTA), we obtain the event number of possible neutrino emissions. The result demonstrates that low-mass microquasars are potential neutrino source, neutrinos from which are likely to be identified with several years of observations from the km^3-scale neutrino detectors. Second, we propose another model extended from jet's base to large jet scale to investigate broadband emission origin, orbital modulation due to the orbital-phase and angular dependence γ-γ absorption. We find that the model can explain multi-wavelength observations of LS I +61° 303 at near the superior and inferior conjunctions. Third, thanks to motivations from Cygnus X–1 observations, we want to know that whether the region of jet termination interacting with ISM can produce high-energy or very high-energy emissions, and whether it is possible for the new generation CTA to detect emission signal. Through developing a double-shock model in this region, we find that the answers above are optimistic and microquasar population is a possible contributor for Galactic cosmic rays.

In the study of the leptonic models (Chapter 3), we develop a two-dimensional, time-dependent radiation model for a high-mass X-ray binary by analogy with the methods used in studies of blazars. We study the spectral properties of electron evolution, its dominant cooling mechanisms and emission spectral characteristic at different heights of the emission region located in the jet. The fitting results are given as follows.

(1) The radio emission signature is from the region extending from the binary system scales to the jet termination. (2) The emissions in the GeV band should be from the distance close to the binary system scales. (3) The TeV band emissions, which could be probed by the upcoming CTA, could be inside the binary system. (4) The MeV tail emissions, which show a strongly linearly polarized signal, are emitted inside the binary system. The location of which is very close to the inner region of the jet.

In the framework of the 2D leptonic model, we study broadband radiation of Cygnus X–3 during the high soft state by injecting piecewise power-law electron distribution. We stress that Cygnus X–3 is a special example violating the traditional paradigm of X-ray binary state transition, that is, there is the presence of jets during the high soft state. We find that the emission region in the Cygnus X–3 jet is different from the universal persistent jets, whose dissipation region only occupies a slice region of jet, that is, emission signal is from highly compact region, which corresponds to the jet height equal to one orbital radius. The results can explain the current multi-frequency observations and also predict the TeV band emission. The model could be tested by a polarization measurement at IR band. In addition, the neutrino survey done recently motivated us to propose a 2D leptonic radiation model of low-mass microquasars. Numerical results show that radiation spectra induced by pure leptons can successfully extend to high-energy and very high-energy bands. We apply this model to GX 339-4 having relatively complete observations available at low-energy band. The results not only can reproduce the currently available observations, but also predict detectable radiation at GeV and TeV bands by the Fermi and CTA telescopes. This model could be employed to distinguish the origin of X-ray emissions.

Under the framework of the magnetized accretion ejection structures, we in Chapter 4 analyse the energy balance properties of the jet-emitting disk (JED) model, and study the spectral energy distributions of the JED model for black hole X-ray transients. With various cooling processes taken into account, we solve the thermal equilibrium equation self-consistently and find three solutions, of which the cold and the hot solutions are stable; they corresponds to geometrically thick and optically thin advection-dominated accretion flow (ADAF), and optically thick and geometrically thin standard disk (SSD), respectively. After investigating the theoretical spectra for these two stable solutions, we find that the hot JED model can naturally explain the spectra of the Galactic microquasars in their hard states. As an example, we apply this model to XTE J1118+480. In addition, we also suggest a radiation model in the magnetospheric gap region of accreting X-ray binary pulsars, in which electrons are accelerated by electric field force. Applying the model to LS I + 61° 303 with a signal of the magnetar, we find that the model can explain the spectral cutoff feature at a few GeV. Therefore, we claim that the high-energy emissions from accreting X-ray binary pulsar system originate in

the magnetospheric region of the pulsar.

In Chapter 5, we use synthetic observations to test analytical predictions of the new statistical techniques. We find that numerical results are in good agreement with theoretical predictions. Based on 3D, 2D and 1D synthetic observations, numerical results we have obtained are briefly summarized as follows. (1) The studies of the polarization dispersion of synchrotron radiation demonstrated that for the region dominated by stochastic rotation measure (RM) fluctuations, the variance of polarization gives the universal slope λ^{-2}. In a region with the dominant RM effect arising from the regular magnetic field, the variance of polarization follows λ^{-2-2m}. Thus, the polarization variance reflects statistics of the magnetic field component perpendicular to the line of sight. (2) The studies of the dispersion of polarization derivative with regard to λ^2 shows a power-law relation, which should reflect the fluctuation statistics of Faraday rotation. (3) The spectral index of relativistic electrons does not change the slope of the polarization frequency analysis (PFA) measure, and thus does not prevent us from extracting spectral properties of magnetic turbulence. (4) The PFA technique can be practically used, as we presented that the effects of angular resolution and inevitable observational noise are not be obstacles for recovering the underlying spectra of turbulence.

We in Chapter 6 summarize the main research results of this PhD thesis, and discuss the prospects of the next research work. First, we will carry out the work about how the high-energy particle is accelerated in X-ray binaries. Second, we will further study the properties of the MHD turbulence and its influence on various astrophysical processes.

Key Words: X-ray binary; Microquasar; Accretion disk; Radiative mechanism; Magnetohydrodynamic turbulence

目 录