X-ray astrophysics of compact objects
by Anna Marishka Krickovich LeRoux

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics
Montana State University

Abstract:
Seyfert galaxies have long been known to exhibit rapid X-ray Variability. As yet, no definitive mechanism for this variability has been identified, but shocks and flare-like events have been suggested as viable possibilities. An ASCA observation of the galaxy NGC 3227 had flares which followed a linear increase and exponential decrease, which is the same pattern followed by solar flares. Using the same techniques previously used to derive scaling laws for solar flares, a scaling law for flares on the accretion disks of AGN is derived. The law relates the loop length to the loop apex temperature, rise time, and decay time of the flare in the light curve, and from the data obtained from the observation of NGC 3227, the flarelike events are consistent with a physically viable region in the parameter space of loop length and apex temperature. Thus, at least by this measure, flares caused by magnetic loops remain a physically viable mechanism for AGN variability.

Observations of Seyfert Galaxies, whether by ASCA or by other satellites, have previously divided the data of long observations by observation time or by luminosity to create spectra which average over one of these. Here an alternative method for classifying bins in the light curve according to hardness is developed, and correlated to the phenomenology of the light curve. This method is applied to the 1994 150 ks exposure ASCA observation of MCG-6-30-15. The results are that, when coupled with very conservative spectral fitting techniques, the new extraction technique suggests that local minima and maxima are spectrally different from other regions of the light curve with the same luminosity. The Seyfert galaxy Arkarian 120 is also analyzed, but has too short an exposure to extract statistically viable spectra. The spectral fitting of this source shows no evidence for a warm absorber, but suggests a soft energy excess due to blackbody radiation.

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MONTANA STATE UNIVERSITY — BOZEMAN
Bozeman, Montana

April 2000

APPROVAL

of a thesis submitted by

Anna Marishka Krickovich LeRoux

This thesis has been read by each member of the thesis committee, and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style and consistency, and is ready for submission to the College of Graduate Studies.

Sachiko Tsuruta, Ph. D. Sachiko Tsuruta (Signature) 4/15/2000 Date

Approved for the Department of Physics

John C. Hermanson, Ph. D. John Hermanson (Signature) 4-15-2000 Date

Approved for the College of Graduate Studies

Bruce McLeod, Ph. D. Bruce R. McLeod (Signature) 4-17-00 Date

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Date April 16, 2000

ACKNOWLEDGEMENTS

I would like to thank a number of individuals who have made the thesis-writing process survivable. I would like to thank Sachiko Tsuruta for her guidance as a thesis advisor, and also Dana Longcope and George Fisher for extensive discussion of solar flares and magnetic reconnection. I would further like to thank Hideyo Kunieda for providing much of the data analyzed in this thesis, and for extremely helpful comments on spectral fitting techniques.

I would also like to thank the large number of additional individuals in physics who have read and critiqued parts of my thesis, particularly, Loren Acton, Jyostna Krishnamoorthi, and Darrell Rilett. I would also like to thank the two non-physicists who have done extensive technical editing for me- my two dads, Jeff LeRoux and Everett Hansen. I would also like to thank my mother for taking care of me during the very last days of writing. Writing in absentia is an undertaking in itself, and I would like to acknowledge those of my colleagues who have been particularly supportive in the more difficult times, Frank Herrmann and Michelle Volken.

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ABSTRACT

Seyfert galaxies have long been known to exhibit rapid X-ray variability. As yet, no definitive mechanism for this variability has been identified, but shocks and flare-like events have been suggested as viable possibilities. An ASCA observation of the galaxy NGC 3227 had flares which followed a linear increase and exponential decrease, which is the same pattern followed by solar flares. Using the same techniques previously used to derive scaling laws for solar flares, a scaling law for flares on the accretion disks of AGN is derived. The law relates the loop length to the loop apex temperature, rise time, and decay time of the flare in the light curve, and from the data obtained from the observation of NGC 3227, the flarelike events are consistent with a physically viable region in the parameter space of loop length and apex temperature. Thus, at least by this measure, flares caused by magnetic loops remain a physically viable mechanism for AGN variability.

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CHAPTER 1

INTRODUCTION

Now you have just been able to reduce the countless embattled troops to an array that is, to be sure, very large but still calculable in a finite number; but this relative relief is undermined by the ambush of the Books Read Long Ago Which It's Now Time To Reread and the Books You've Always Pretended to Read And Now It's Time To Sit Down and Really Read Them.

(Italo Calvino, **If on a Winter's Night a Traveler**)

Introduction

In 1962 Giacconi discovered X-rays from Scorpius X-1 (Giacconi *et. al.* 1962), marking the beginning of X-ray studies of compact objects. While Cygnus X-1 is thought to consist of an accretion disk orbiting a Galactic black hole of less than $20M_{sun}$, the accretion disks orbiting the 10^8 solar mass black holes thought to exist in the centers of active galaxies, which include quasars and Seyfert galaxies, can also be analyzed in the X-ray window. These galaxies are characterized by their bright nuclei, which typically have luminosities between 10^{41} erg s^{-1} and 10^{47} erg s^{-1}, of which a large fraction occurs in the X-ray spectral region. The generally accepted disk-corona model suggests that the disk is surrounded by a hot corona, and hard X-rays are produced by inverse Compton processes on the lower energy photons from the disk.

Seyfert 1 galaxies are a relatively quiet relation in the family of active galaxies, having luminosities near 10^{44} erg s^{-1} in the X-ray band, broad permitted and narrow forbidden optical lines, and relatively weak radio emission. Seyfert 2 galaxies typically show only forbidden transitions in the optical region and exhibit strong emission in the UV. Seyfert 1 galaxies are related to the brighter Quasi-Stellar Objects (QSO) in that they are radio-quiet and typically associated with spiral galaxies, although QSO's generally have X-ray fluxes one or two orders of magnitude larger than Seyfert 1 galaxies and tend to be located at higher redshift. Quasi Stellar Radio Sources (QSR's) are radio-loud, but are as bright as QSO's and have broad lines. Both kinds of Seyfert galaxy, QSO, and QSR are associated with spiral galaxies. Radio galaxies are radio-loud, and are often associated with giant elliptical galaxies. BL Lacertae objects, named after the first known example, are galaxies with very few broad emission lines, and vary rapidly ($\tau < 1$ day) in both the optical and X-ray. LINERS (Low Ionization Nuclear Emission-Line Regions) show lower ionization states than do other AGN, and are often associated with elliptical galaxies. Generally, radio galaxies, BL Lac galaxies, and Optically Violent Variables (OVV's) are associated with elliptical or S0 galaxies, while QSO's, QSR's and both flavors of Seyfert galaxies are associated with early spiral galaxies (Woltjer, 1990). Starbursts galaxies are associated with both spiral and elliptical morphologies (Aretxaga, 1996).

X-ray Observation of Seyfert Galaxies

In the 1970's, X-ray observation was done with temporary missions on satellites. Such missions discovered X-rays from 3C273, the first AGN to show X-ray emission (Bowyer *et. al.*, 1970). HEAO-1 was launched in 1977, and provided the first map of the X-ray sky. In addition, the telescopes of HEAO-1 made the first measurements of the X-ray spectra of quasars and Seyfert galaxies, showing the now well known power-law spectrum they exhibit in that spectral window. In 1978, the Einstein observatory was launched. Spectra from Einstein had emission lines which were noticeably red-shifted from their nominal values; from this, researchers concluded that AGN are receding. In addition, the first evidence of fluorescence from cold iron was observed in Centaurus A (Mushotzky *et. al.* 1978).

A spectral survey performed by EXOSAT showed that AGN had a 2–10 keV spectrum which was well-described by a simple powerlaw model, but had rapidly varying soft energy features and "leaky" absorption columns (Turner and Pounds 1988); that is, absorption columns which only partially cover the continuum radiation. The photon index of the 48 measured AGN was found to be $\Gamma = 1.7 \pm 0.17$, with a few outlier objects. GINGA observations of Seyfert galaxies provided the first measurement of the iron Kα emission line and the cold reflection hump. These two features are thought to originate on the innermost accretion disk; the ionized iron line provides information about the ionization state of the disk, and the reflection hump size is directly proportional to the column density of material in the disk and the solid angle Ω of the thickness of the disk. ROSAT was designed to measure soft X-rays from AGN and neutron stars; observations with ROSAT first showed the presence of a large neutral hydrogen column in the line of sight of many AGN. This hydrogen column is thought to exist mostly in our own galaxy, with an excess occurring in the interstellar medium and in the outer regions of the AGN itself.

Unified Model of Active Galactic Nuclei

While it has been postulated that interactions with neighboring galaxies play some role in the origin of AGN, at least some studies suggest that the occurrence of Seyfert galaxies with close companions is no higher than for normal galaxies (de Robertis *et. al* 1998). In order to explain the differences between varieties of AGN, the *Standard Model* of AGN has been developed (see, for example, Rees,1997). The underlying premise of the standard model is that the structure of all active galaxies is the same: the hard X-rays and γ-rays are produced from an inner accretion disk, which runs perpendicular to the radio jets produced by the object. The inner accretion region is surrounded by a plasma which absorbs and reflects the continuum, referred to as the broadline region (BLR), which is in turn surrounded by a torus of molecular gas. Outside this torus lies the narrowline region (NLR), which consists of a less dense plasma. Outside this lie the nebulae and stars which comprise the outer regions of all galaxies. This model is illustrated in Figure 1.1.

Seyfert galaxies and quasars are thought to form the class of objects with high accretion rates, while radio galaxies are thought to form the class of objects for low accretion rates. LINERS are thought to correspond to rare objects for which we are viewing the galaxy directly along its rotation axis, which dominates the continuum

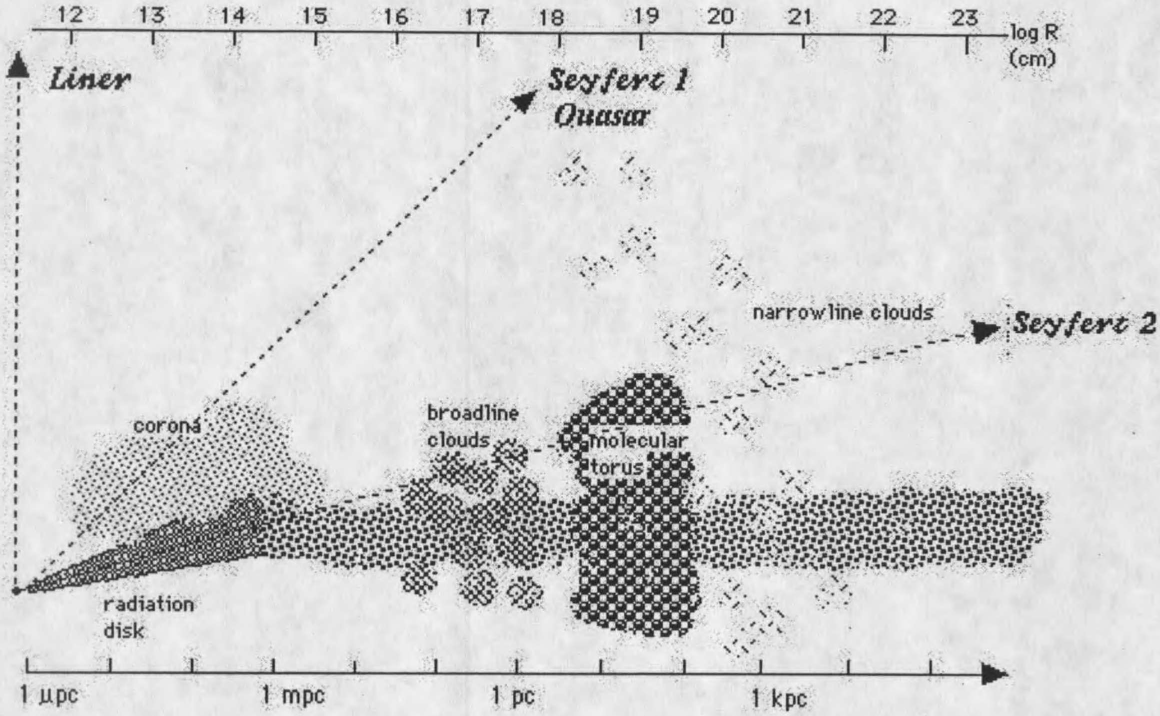

Figure 1.1: Unified Model for Active Galactic Nuclei.

radiation. Seyfert 1 galaxies and QSO's correspond to viewing angles which vary from just off the line of sight of the jet to just grazing the broadline clouds of the galaxy. Seyfert 2 galaxies correspond to high viewing angles (close to edge-on) which require photons to travel through the molecular torus, although the dearth of high-luminosity Seyfert 2 galaxies suggests that molecular tori are thin or unstable under such conditions (Osterbrock, 1993).

More recently, the broadband continuum of some members of the AGN family has been modeled with advection dominated accretion flows, in which the high-energy radiation is produced from the disk itself. The presence of the iron Kα emission line and the Compton reflection hump in Seyfert 1 galaxies strongly contraindicates that their accretion disks are advection-dominated (Ptak *et. al.*, 1998), so the objects observed in this work are analyzed with reference to the standard α disk model (Shakura and Sunyaev, 1973).

While aesthetically pleasing, the standard model does have some inconsistencies with observation. Seyfert 2 galaxies have a far stronger UV continuum and a far weaker hard X-ray continuum than one would predict from reasonable models of the torus of molecular clouds, suggesting that they have less active central engines and more active star forming regions than do Seyfert 1 galaxies. In addition, careful study of the environments of Seyfert galaxies indicates that Seyfert 2 galaxies are far more likely than either Seyfert 1 galaxies or an equivalent population of normal galaxies to have large companion galaxies, suggesting that tidal interactions, and not only obscuration of the BLR and nucleus by a molecular torus, may play a part in the formation of Seyfert 2 galaxies (Dultzin-Hacyan *et. al.*, 1999).

X-ray Variability of AGN

The X-ray continuum of many AGN varies by a full factor of 100 % of its baseline value over timescales of hours. The X-ray and UV spectra of most AGN are variable (Elvis *et. al.*, 1978). A recent study of 24 Seyfert 1 galaxies found that most varied significantly (Reynolds, 1997). Typical X-ray variability of a Seyfert galaxy is shown in Figure 1.2, which shows a 1993 observation of NGC 4593.

The exact mechanism of the rapid X-ray variability in AGN is not known. One theory was that hot spots on the accretion disk were orbiting the black hole with some angular velocity as they accreted material, thus causing variations in the X-ray luminosity. Were this the case, we would expect to see a periodic component in the

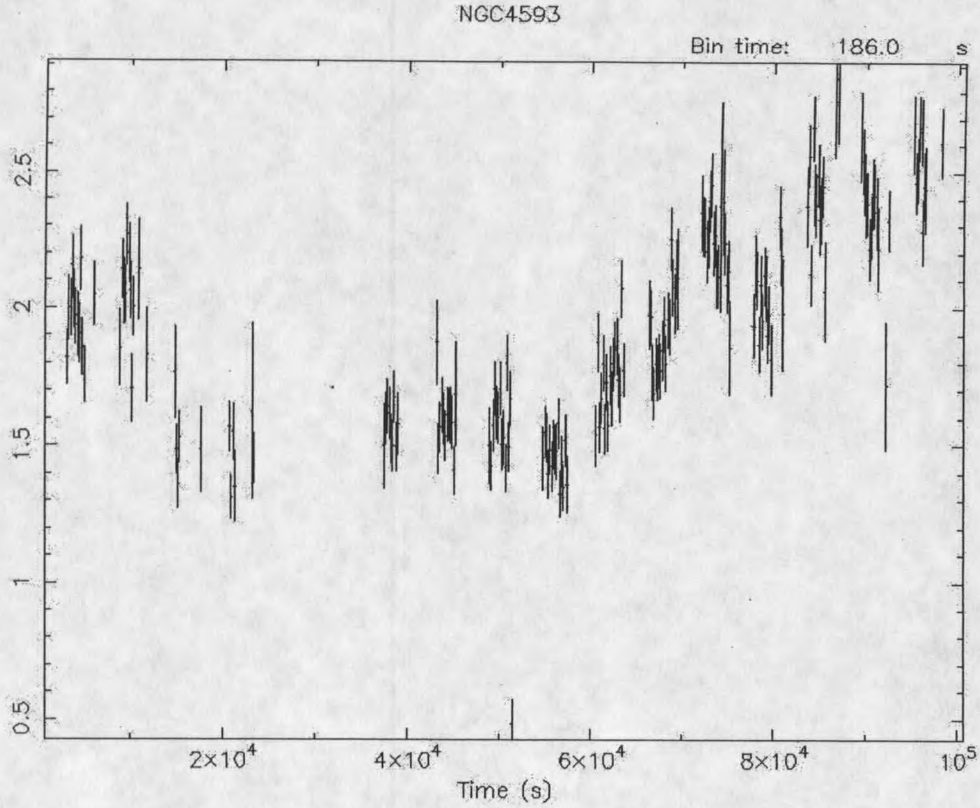

Figure 1.2: Light curve of NGC 4593. The flare maximum is double the baseline luminosity of the galaxy. This light curve was made by the author from an archival ASCA observation of NGC 4593.

power spectrum of the X-ray light curve which was associated with the rotational period of such a hot spot, and this is emphatically contrary to observation (Kuras, 1997). Another possible source of the variation is ionizing shocks which move through the accretion disk (Caditz, Tsuruta, Sivron 1997); this possibility is still viable and may prove to be the source of variation in many objects. Another possibility is that magnetic flux tubes in the AGN's radiation disk are pushed out of the disk by buoyancy forces, creating a tube of hot plasma similar to those which host flares in the solar corona. This possibility was first explored by Rosner, Tucker and Vaiana (1978). who hypothesized that the corona of an accretion disk around a Galactic black hole such as Cygnus X-1 consists of a forest of flare loops anchored in the accretion disk.

Solar and stellar flares have well-studied scaling laws which relate the loop length L to the temperature T of the loop plasma and the rise and decay times of the flare, represented by τ_R and τ_D respectively. These are based on assumptions about the energy balance of the loop plasma during various stages of the flare (Fisher and Hawley, 1990) and have also been found to apply to at least one X-ray star (Hawley *et. al.* 1995). The scaling law for stellar and solar flares is (Metcalf and Fisher, 1996):

$$2L = 0.0126\tau_R^{3/7}\tau_D^{4/7}T^{1/2}, \tag{1.1}$$

so longer loops of the same temperature have longer rise and decay times. This scaling law is based on cooling by thermal bremsstrahlung alone in a region of plasma cooling curve where the photon emissivity is proportional to $T^{1/2}$ (Raymond and Smith, 1977). The hotter, denser plasmas expected from models of AGN radiation disks would not only have a different dependence of emissivity on temperature, they would also have the additional cooling mechanism of inverse Compton scattering. These two factors give rise to a new scaling law for AGN flare loops.

The X-ray spectrum of at least some AGN also varies during luminosity changes. Galactic black hole candidates show five distinct states during a flare cycle which can be explained by a magnetic reconnection model of flares (Di Matteo, Celotti, and

Fabian, 1998), but as yet the X-ray variation of AGN does not follow such a simple pattern. The warm absorber of the Seyfert 1 galaxy MCG-6-30-15 has been seen to vary during luminosity variations (Otani *et. al.*, 1995) as has the Iron Kα line (Tanaka *et. al.*, 1995).

In this work, a new scaling law is derived for AGN flares and used to predict the loop length of a magnetic flux tube associated with two large flares during an ASCA observation of NGC 3227, discussed in Chapter 2 of this work. This loop length allows us to evaluate the feasibility of reconnection of magnetic flux tubes as a mechanism of AGN variability in terms of energetics, pressure balance, and consistency with spectral (non-) variability of the AGN continuum slope during flares.

Structure of the Warm Absorber and Broadline Region

ROSAT observations first showed the presence of O VIII absorption in the soft X-ray spectrum of Seyfert Galaxies (Nandra and Pounds, 1992). Outside the inner accretion disk and its corona lie the broadline clouds. Since they exhibit a variety of emission and absorption features, optical spectra of the broadline region can be used to study the composition of the broadline plasma. When ASCA was launched in 1993, the soft X-ray region from 0.5–2.0 keV of many Seyfert 1 galaxies showed two absorption edges; one near 0.87 keV corresponds to O VIII and another near 0.72 keV corresponds to O VII (Ferland, 1993). The plasma containing these lines was duly christened the warm absorber. In early analysis, the warm absorber was thought to be located near the broadline region, 10^{18} cm from the central black hole.

A variety of analytical tools are available for analyzing the warm absorber. Studying the variation of individual line features is one means of doing this; from the timescale of variation of a spectral feature, we can infer the maximum distance between that feature and the central black hole. A macroscopic plasma cannot change state faster than the light-crossing time of the plasma, so the maximum radius, R_{max}, of a plasma which varies on a minimum timescale τ must be:

$$R_{max} = \frac{c}{\tau}. \tag{1.2}$$

As plasma could hypothetically vary more slowly than the light-crossing time as well, so lack of variation of a spectral feature on a particular timescale does not necessarily require that it is located further from the nucleus than the light crossing time.

The exact structure of the warm absorber is also an open research question. Most studies to date have suggested that the warm absorber is one (presumably inhomogeneous) region of gas and dust spanning a radial region from 10^{14} cm to 10^{17} cm from the central black hole. Timescale variations of O VII and O VIII in MCG-6-30-15 suggested that the warm absorber had two distinct regions, one located 10^{17} cm from the central black hole and containing O VIII and the other located 10^{19} cm from the central black hole containing predominantly O VII (Otani *et. al.* 1995). The argument here was based not only on the timescale of variation of each oxygen edge, but also on the recombination physics of O VIII; had the two been located in the same region, O VII would decrease during periods of increased luminosity as it was promoted to O VIII, although the timescale of recombination, which is much larger than that of ionization, limits the probability that an increase in O VII could be rigorously correlated to luminosity changes. No other AGN with similar warm absorber structure has been identified to date.

In addition, a variety of photoionization codes are available for modeling, including the widely used CLOUDY (Ferland, 1996), the less dominant ION (Netzer 1993), and the shock treatment of MAPPINGS (Dopita *et. al.* 1995). These models all produce at least two variable parameters when translated into a model for data analysis; first, an ionization parameter, which is defined as:

$$U_x = \int_{0.1keV}^{10keV} \frac{Q(E)}{4\pi n_H r^2} dE \qquad (1.3)$$

by ION, where Q(E) is the radiation density at energy E, n_H the equivalent hydrogen density, and r the distance of the absorptive material from the central engine. The other variable in all of these codes is the column density of photoionized gas, N_h. Many models also contain other parameters, such as the composition of the plasma, the shape and filling factor of the gas, and the photon index of the continuum spectrum which causes the ionization. In this work, we use ION as a one-zone photoionization model of the warm absorber region because it is valid for plasmas closer to the inner accretion disk than are any of the other models.

Contents of this Work

In this thesis, we will attempt to discuss some of the open issues regarding the structure and dynamics of Active Galactic Nuclei discussed above by analyzing ASCA