Dramatic X-ray Variability in AGNs: New Insights into Black Hole Fueling

by

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The Prototype (TIE Advanced x1)

ROSAT PSPC

art by: Benjamin Cassi
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\(^1\)His words not mine.
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Chapter 1

Introduction

From studies of nearby galaxies and distant quasars, it is now widely accepted that most or all large galaxies contain a supermassive black hole (SMBH) with a mass ranging from $10^6 - 10^9 \, M_\odot$ in their center (Volonteri 2010; Ferrarese & Ford 2005). However, it is not currently understood how these SMBHs were formed or have evolved to such large masses. A number of studies have found linear correlations between black hole mass ($M_\bullet$) with the stellar velocity dispersion ($\sigma$), mass ($M_{\text{bulge}}$), and luminosity ($L_{\text{bulge}}$) of a galaxy’s classical bulge, suggesting that BH evolution might be tied somehow to galaxy evolution (Ferrarese & Merritt 2000; Bentz et al. 2009; Kormendy & Richstone 1995; Gültekin et al. 2009; see Figure 1.1). However, a direct connection is unlikely: SMBHs only represent a small fraction of a galaxy’s mass, and consequently, their gravitational influence extends to only a few tens of parsecs from the nucleus. In terms of gravity, the galaxy does not know there is a SMBH in its center, and the black holes does not know that it is living in a galaxy. Thus, these findings favor the possibility that galaxies and their SMBHs evolve via common processes.
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![Correlation diagrams](image)

**Figure 1.1:** Correlations between the mass of the black hole and its host galaxy (from Kormendy & Ho 2013). (a): $M_\bullet - L_{\text{bulge}}$ (b): $M_\bullet - \sigma$ (c): $M_\bullet - M_{\text{bulge}}$. Since these correlations are determined from observations of ellipticals (gray) and classical bulges (red), galaxies with pseudobulges (blue) lie below the line. This shows that those galaxies are built differently, which would indicated a different type of co-evolution.

Over the past two decades, much effort has been directed at understanding black hole/galaxy co-evolution. Kormendy & Ho (2013) have described two forms of co-evolution: weak and strong. In the weak form, the galaxy directly affects the evolution of its black hole through global galaxy-wide processes, whereas in the strong form the black hole affects the galaxy’s evolution via energy and momentum feedback. The $M_\bullet - \sigma$, $M_\bullet - M_{\text{bulge}}$ and $M_\bullet - L_{\text{bulge}}$ linear correlations supports the weak and the strong forms, however, studies have shown that both galaxies
and black holes grow from *gas-rich* mergers (i.e. weak co-evolution; Kormendy & Ho 2013; Hopkins et al. 2008).

When galaxies merge, their SMBHs may eventually merge as well, resulting in a more massive BH. However, several simulations have shown that mergers of gas-rich galaxies can funnel gas to the SMBHs, causing them to grow via accretion at a high rate (Volonteri et al. 2003). Di Matteo et al. (2005) simulated galaxy-galaxy interactions during mergers to investigate the relationship between the accretion growth and the coalescence of their respective SMBHs. Figure 1.2 (from Di Matteo et al. 2005) shows the increase of black hole mass over the course of a merger event. It’s clear that even before the two galaxies pass through one another the first time, SMBHs experience some mild accretion growth. Regardless of virial velocities (80, 160, 320 km s$^{-1}$) or initial galaxy masses, most of the growth occurs after the two black hole merge at 1.6 Gyr; it is primarily the “rapid phase of accretion close to the Eddington ratio” that causes the black holes to become more massive. Di Matteo et al. (2005) note that the merger remnant would appear as a luminous quasar (QSO) until the SMBH accretes above the Eddington luminosity, and drives the material away. In the simulations, the QSO phase lasts from $10^7 - 10^8$ years, which is consistent with the idea that accretion events in QSOs are episodic (Di Matteo et al. 2005; Treister et al. 2012).
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That fact that only a few percent of galaxies contain actively accreting SMBHs, also suggests that SMBH accretion is episodic rather than continuous (Treister et al. 2012). A few scientific questions then arise, such as: What is the duration of these episodes? What fraction of time are these SMBHs “on” or actively accreting? The answers are directly related to the mechanisms by which SMBHs are fueled. The next few sections describe different types of accreting SMBHs and a new approach to addressing these questions.

1.1 The AGN Phenomenon

SMBHs that are actively accreting are also called Active Galactic Nuclei (AGNs). These SMBHs are surrounded by an accretion disk that converts gravitational potential energy to thermal energy and radiation, resulting in luminous X-ray and Ultraviolet radiation. The X-ray and UV radiation photo-ionizes nearby gas that produces emission lines in their optical spectra (Ho 2008).
The emission lines include Doppler-broadened lines that come from two distinct regions in the nucleus: a Broad-Line Region (BLR) that contains gas within \( \sim 1 \) parsec of the SMBH and a Narrow-Line Region (NLR) that can extend from tens to hundreds of parsecs beyond the nucleus. Broadened permitted lines such as H\( \alpha \) and H\( \beta \) arise in the BLR and have full-width at half-maximum (FWHM) of thousands of kilometers per second, while the narrow permitted and forbidden emission lines, produced in the NLR, typically have FWHMs of hundreds of kilometers per second. Some AGNs have spectra that display both line sets (type 1), while other AGNs only have narrow lines (type 2). Additionally, there are intermediate types of AGNs that do not have a broad H\( \beta \) emission line but have a weak H\( \alpha \) line (Osterbrock 1991).

These differences in each type of AGN can be described by different mechanisms, such the obscuration of the BLR or the lack of a BLR due to low-Eddington rates (see §1.2.1). Most, if not all, AGNs are thought have a “torus” that is capable of obscuring the BLR for edge-on viewing angles and rendering the spectrum as one of a type 2 AGN (Antonucci 1983, 1984, 1993). This result comes from spectropolarimetry studies in the 1980s, primarily by Antonucci 1983, 1984, 1993. This result comes from spectropolarimetry studies in the 1980s, primarily by Antonucci (1983, 1984), Antonucci & Miller (1985), and Antonucci (1993).

The Antonucci & Miller (1985) study used spectropolarimetry to look at the polarized light of a type 2 Seyfert galaxy, NGC 1068 (Figure 1.3). The total-flux optical spectrum showed one of a type 2 Seyfert galaxy: the red region of the spectrum has a broad H\( \alpha \) line, and the blue side of the spectrum showed no signs of a broad H\( \beta \) line. However, the polarized light shows a much different AGN: one with a broad H\( \beta \) emission line as in normal type 1 Seyfert galaxies with a full-width at zero-intensity of about 7500 km s\(^{-1}\) (Antonucci & Miller 1985).
Antonucci & Miller (1985) suggested that an optically thick “disk” (later “torus”) is responsible for the polarization results. Since the NLR does not seem to be affected, the medium must only be “hiding” or surrounding the BLR and the continuum (Antonucci & Miller 1985; Antonucci 1993; see Figure 1.4). Emission traveling parallel to the axis of the torus can be scattered into our line of sight, which can be detected using polarization-sensitive optics. Thus, the main difference between type 1 and type 2 could simply be the orientation of the torus to our line of sight. For type 2 Seyfert galaxies, the torus is edge-on, and for type 1, the torus is face-on (Stephens 1989).
However, not all type 2 Seyfert galaxies display evidence for a hidden broad line component; thus, they may actually be “bare” (Denney et al. 2014). Furthermore, the drastic change in luminosity and the disappearance of the broad H$_\beta$ line component could be caused by the AGN accretion “turning-off.” In this circumstance, the BLR would cease to be ionized shortly afterward, but the more excited NLR would continue to be illuminated by ionizing radiation for years or decades. In general, AGNs that exhibit these drastic changes in luminosity and spectroscopic classification are called “Changing-look AGNs” (CLAGNs). CLAGNs may be the key to answer the questions posed above; i.e. How do SMBHs evolve? What is the typical duration of the active phase?
1.2 “Changing-Look” AGNs

In addition to spectroscopic classifications based on emission lines, luminosity can also be a way to classify AGNs. Seyfert galaxies are AGNs that are typically less luminous than their host galaxies. Their spectra are usually composed of combined emission from both the host galaxy and the nucleus. QSOs are bright enough optically to drown out the light from their host galaxies, which allow them to be detected at higher redshifts. Recently, a handful of AGNs, in both luminosity categories have demonstrated CLAGN behavior.

1.2.1 Markarian 590

Mrk 590, $z = 0.026$, is a Seyfert 1 galaxy that has been observed over the span of 40 years (Figure 1.5). In 1973, its spectrum was that of an intermediate type 1.5 Seyfert galaxy; there was no evidence of a broad H$\beta$ line, but it had a weak, broad H$\alpha$ emission line. However, in 1989, a strong broad H$\beta$ line appeared, and both the H$\alpha$ line and luminosity increased, changing the AGN classification from an intermediate type to a classical type 1 Seyfert galaxy (Denney et al. 2014). However, after 1996, the H$\beta$ and H$\alpha$ emission lines became more narrow, and in 2006, the broad H$\beta$ line completely disappeared, rendering the AGN a type 1.9 Seyfert galaxy (Denney et al. 2014). Thus, the disappearance of H$\beta$ may have indicated the disappearance of the BLR, which can be explained by the decrease in accretion rate (Ho 2008; Denney et al. 2014).
The BLR is thought to disappear at low Eddington ratio, thus a large change in accretion could diminish the BLR (Ho 2008; LaMassa et al. 2015; Denney et al. 2014). Furthermore, to calculate the bolometric luminosity of a BH of $\sim 10^7 M_\odot$, Denney et al. (2014) used the 2014 monochromatic continuum luminosity at 1450 Å, a conversion factor of 4.2, a “mean “Low Luminosity” AGN SED template” with a percentage of $L_{\text{bol}}$ below 912 Å. The bolometric luminosity revealed that Mrk 590 is accreting below the minimum accretion rate needed to maintain a BLR by a factor of $\sim 2.9$ (Denney et al. 2014; Runnoe et al. 2012; Krawczyk et al. 2013; Nicastro 2000). These findings can either be described as an AGN “turning-off” or as proof that the Doppler broadened emission lines and the accretion phenomenon are episodic in nature (Denney et al. 2014; Ruan et al. 2016).

**Figure 1.5:** The de-redshifted spectra of Mrk 590 (from Denney et al. 2014). The Hβ line narrows down by the 2006 spectra, and completely disappears by 2014. Like J0159+0033, the Hα line narrows, but remains somewhat broad. The red line is a fitted a host galaxy template, and the blue is a power law fit to the continuum.
Another Seyfert galaxy that has presented similar behavior to Mrk 590 is Mrk 1018. In the span of 30 years, it went from a type 1.9 Seyfert galaxy to a type 1 Seyfert galaxy and then back to a type 1.9 Seyfert galaxy. However, unlike Mrk 590, Mrk 1018 is in a late-state major merger, which might imply that a nearby SMBH is altering the dynamics of the BLR (McElroy et al. 2016).

As more CLAGNs are found, they seem to have both similar and different features when compared to Mrk 590. The next section will talk about the first QSO that was found to be a CLAGN.

### 1.2.2 SDSS J015957.64+003310.5

SDSS J015957.64+003310.5, or J0159+0033 ($z = 0.31$), was the first QSO found to have transitioned from a luminous type 1 AGN to a type 1.9 AGN. J0159+0033 has been observed thrice in the optical by the time of the LaMassa et al. (2015) study: Once in 2000 by SDSS (Sloan Digital Sky Survey), again in 2010 by SDSS-III BOSS (Baryon Oscillation Spectroscopic Survey), and lastly in 2014 using DBSP (the Double Spectrograph) on the Palomar 5m telescope. As seen from the spectra in Figure 1.6 the H$_{\beta}$ line at 4861 Å was broad in 2000, with FWHM=5043±466 km s$^{-1}$. However, at later epochs, the broad component is completely gone, while the other broad emission line, H$_{\alpha}$, is still broad but considerably weaker. The spectra for 2010 and 2014 are consistent with the spectrum of type 1.9 AGN (Osterbrock 1981).
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Furthermore, using the monochromatic luminosity at 5100 Å ($\lambda L_{5100} = 1.09 \pm 0.01 \times 10^{44}$ erg s$^{-1}$) and bolometric correction of 8.1, LaMassa et al. (2015) were able to calculate the bolometric luminosity for the 2000 and 2010 observations (Runnoe et al. 2012). The bolometric luminosity dimmed from $8.8 \pm 0.01 \times 10^{44}$ erg s$^{-1}$ to $1.6 \pm 0.01 \times 10^{44}$ erg s$^{-1}$, by a factor of 5.5, consistent with the dimming of its X-ray luminosity. *XMM-Newton* and *Chandra* data obtained contemporaneously with the two main epochs showed that the 2-10 keV flux of the QSO dimmed by a factor of 7.2. Since both the X-ray and optical luminosity dimmed by similar amounts, and given that X-ray variability directly correlates with changes in accretion, it is more likely that the AGN dimming is due to a
change in accretion (LaMassa et al. 2015).

However, if the results were due to “variable absorption,” then two different types of clouds would be required: a dust cloud of low optical depth that obscures the broad line region, and a gas cloud of high optical depth that would reduce the X-ray emission. These two clouds would need to reduce the emission at the two different wavelengths by roughly the same amount, which seems highly unlikely (LaMassa et al. 2015).

But could the results instead be explained by a tidal disruption event (TDE)? Merloni et al. (2015) argue that these the changes in X-ray and optical luminosity could be explained by the TDE of a supermassive star that passed by the event horizon of the SMBH. If the QSO flared before the spectrum for 2000 was taken, it could explain why the bolometric luminosity and the X-ray luminosity has decreased by the same amount. Their model of the system showed that the Spectral Energy Distribution (SED) of the “flare” seems to match the SEDs of other reported flares. Additionally, since QSOs are the most luminous type of AGN, it is not easy for them to deplete their resources and “turn off.” Nevertheless, more data will help distinguish a clear long-term trend from a simple flare and help scientists understand the CLAGNs in general and find other examples more efficiently.

1.2.3 Other CLAGNs

Most of the CLAGNs have been discovered in optical systematic searches using the Sloan Digital Sky Survey. Some of them were cross-checked in X-ray surveys to check for similar trends (LaMassa et al. 2015; Ruan et al. 2016; Runnoe et al. 2016; MacLeod et al. 2016; Rumbaugh et al. 2017). Recently, some AGNs have
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Gezari et al. (2017) found a broad-line QSO at \( z = 0.237 \) “turning-on.” SDSS J155440.25+362952.0, or iPTF 16bco, was rediscovered as a transient object by the intermediate Palomar Transient Factory (iPTF)\(^1\). Its 2004 SDSS spectrum showed the characteristics of a low-ionization emission line region (LINER). LINERs are less luminous than Seyfert galaxies (Ho 2008). The spectrum taken with the Keck 10m telescope spectrograph, in 2016, did not appear to be one of a LINER but rather one of a broad-line QSO. Furthermore, its X-ray and UV data showed an increase in flux by a factor greater than 10 in less than a year in the QSO rest-frame. The increase of both the UV and X-ray data makes it more probable that the variability is associated with an increase in accretion, rather than variable obscuration (Gezari et al. 2017).

Sheng et al. (2017) have reported large mid-infrared variability for 8 CLAGNs with WISE (Wide-field Infrared Survey Explorer)\(^2\). They argued that because infrared radiation is “less affected by dust extinction than optical radiation,” it would rule out variable obscuration. Furthermore, they selected CLAGNs that transitioned from a type 1 to a type 2, and vice versa, two of which are mentioned in this paper: Mrk 1018 (§1.2.1) and J1554+3629 (§1.2.2). Mrk 1018 showed a similar decline, greater than 10\( \sigma \), in its mid-infrared data and its optical data, whereas J1554+3629 showed a “remarkable” increase in the mid-infrared, which compliments its transition to a broad-line QSO (Sheng et al. 2017).

Moreover, motivated by the rapid transition of J1554+3629 and J1011+5442, Yang et al. (2017) have discovered 21 new CLAGNs (0.08 < \( z < 0.58 \)). First they examined SDSS data, then cross-checked it with WISE data, and inspected any

\(^1\)it’s a wide-field optical survey
\(^2\)Including CLAGNs from: MacLeod et al. (2016); McElroy et al. (2016); Runnoe et al. (2016); Gezari et al. (2017)
available spectra. Of the 21 new CLAGNs, 15 “turned-on,” while 6 “turned-off.” They noted that high-accuracy spectroscopy data is needed to determine their AGN classifications, but generally, the types range from type 1 to type 1.8-2, and vice versa (Yang et al. 2017).

Most CLAGNs have been found by searching for photometric variability in large optical surveys, despite that fact that they also show dramatic variation at other wavelengths: UV, X-ray, and IR. Therefore, it may be beneficial to employ long-term X-ray variability to identify CLAGN candidates.

1.2.4 Our Approach

Unlike some other types of radiation, strong X-ray emission is a direct consequence of black hole accretion, suggesting that dramatic long-term X-ray variability may provide insight into the processes by which AGNs are fueled. Thus, we search for variable sources in X-ray data sets from the Einstein, ROSAT, Chandra, XMM-Newton, and ASCA observatories, which span the entire history of imaging X-ray astronomy (Chapter 2). To gain a deeper understanding of these variable sources, we obtained images and spectra of their optical counterparts with the Palomar 5m telescope (Chapter 3). Furthermore, long-term X-ray light curves are created for identified variable broad line AGNs or BLAGNs (Chapter 4). These BLAGNs provide new insights into the CLAGNs phenomenon and into the question of BH fueling (Chapter 5).
Chapter 2
Experimental Design

It is rare to catch AGNs in the act of “turning-off,” or changing its accretion rate because of their relatively long lifetimes. To maximize the detection rate of “Changing-look” AGNs, we must maximize the time intervals between each X-ray observation. Thus, the Einstein Observatory launched 40 years ago is a great starting point. The next step would be find another mission launched 10 years later. Fortunately, there are a few, but due to their small field-of-view, Chandra and XMM-Newton have only surveyed a small fraction of the celestial sphere. Therefore, we focused on data from the German satellite, RÖntgen SATellite or ROSAT, which performed an all-sky survey in 1990. The next few sections will provide more details about these two observatories, their respective source catalogs, and the results of the cross-correlation of those catalogs.

2.1 The Einstein Observatory

Although, the Einstein was the second of NASA’s High Energy Astrophysical Observatories, it was the first imaging X-ray telescope to observe faint X-ray sources over a significant portion of the sky. It was launched on Nov 12, 1978, approximately 12 years before the ROSAT satellite. Einstein’s instruments include a type I Wolter X-ray telescope that used grazing incident optics to form images,\(^1\)

\(^1\)It had four pairs of nested mirrors, each consisting of a parabolic primary and a hyperbolic secondary. X-rays graze the parabolic mirrors, and then the hyperbolic mirrors before converging
and a focal plane transport assembly that set the focus from one instrument to another, such as the Imaging Proportional Counter (IPC; Giacconi et al. 1979). The *Einstein* IPC was the most widely used instrument. It had a $\sim 1^\circ \times 1^\circ$ field of view, and combined with its optics, it had an angular resolution of $\sim 1'$ and was sensitive in the $\sim 0.1$-4 keV range. A couple of serendipitous source surveys used data from *Einstein* IPC, such as the moderately deep Medium Sensitivity Survey (MSS; Stocke et al. 1983), and the Extended Medium Sensitivity Survey (EMSS; Gioia et al. 1990). Most of these surveys aimed to characterize sources at high Galactic latitudes in order to investigate the nature of both Galactic and extragalactic populations and their contribution to the cosmic X-ray background (see Figure 2.1; Gioia et al. 1990).

![Figure 2.1: Map of the X-ray sources from the EMSS (from Gioia et al. 1990)](image)

As more teams conducted analysis of data from the *Einstein* IPC, better characterization of the instrument permitted a decrease in the signal-to-noise threshold at the focal surface (Giacconi et al. 1979).
old for reliable source detection from $5\sigma$ to $3.5\sigma$. In order to study even fainter sources, Moran et al. (1996b) reduced the threshold down to $2\sigma$. In their Two-Sigma Catalog, a source-search algorithm similar to that developed by Hamilton et al. (1991) was employed. Two things were done to extract more information from the IPC database: (1) The sky area searched in each image was increased to $\sim 0.75 \text{ deg}^2$ compared to the $0.6 \text{ deg}^2$ in the EMSS; (2) Many more *Einstein* IPC fields were included (2520 vs. 242 in the EMSS; Moran et al. 1996b). In addition, the source search technique was modified to improve accuracy and decrease the number of spurious sources. The procedure involved the creation of two maps for each *Einstein* IPC observation, one for the counts and another for exposure time. To account for vignetting, the exposure map was corrected for the *Einstein* IPC flat field. Then, the data (0.16-3.5 keV) was binned in $32'' \times 32''$ pixels, allowing for a better spatial sampling than that employed previously ($64'' \times 64''$). The final step was to align all of the maps in sky coordinates and combined them prior to searching for sources.

To search for sources in the *Einstein* IPC images, the signal-to-noise ratio was computed for each pixel in the image using background measurements in a concentric annulus. The search was performed iteratively, starting with a detection threshold of $10\sigma$ and eventually reducing it to $2\sigma$. Whenever the calculated signal-to-noise ratio was larger than the threshold, the source was cataloged and then “deleted” from the image in order to reduce possible contamination in subsequent source-search iterations. After examining 2520 high-latitude *Einstein* IPC fields, this process resulted in 46,186 sources and fluctuations above $2\sigma$, $\sim 13,000$ of which are expected to be real celestial X-ray sources based on the soft X-ray log($N$) – log($S$) relation (Moran et al. 1996b). As discussed in Chapter 4, some of these 13,000 sources have turned out to be dramatically variable AGNs based
on comparison between the *Einstein* Two-Sigma catalog and the data from the *ROSAT* All-Sky Survey.

2.2 The ROSAT All-Sky Survey

On Jun 01, 1990, the Max-Planck-Institut für extraterrestrische Physik (MPE) launched an X-ray satellite called *ROSAT* into orbit. One of the main goals of the mission was to conduct the first X-ray survey of the entire sky in the extreme ultraviolet (0.025-0.2 keV) and in the soft X-ray (0.1-2.4 keV) bands that would improve source position accuracy and increase sensitivity over previous instrumentation (Trümper 1982). Some aspects of the *ROSAT* design were similar to that of *Einstein*. For example, it also had a type I Wolter telescope (XRT) with a carousel that was able to put different instruments at the telescope focus. Unlike *Einstein*, *ROSAT* had a British built EUV telescope ("wide-field camera" or WFC) and two redundant position sensitive proportional counters (PSPCs), instead of one.

The instruments on board the satellite were switched on 16 days after the launch, but a period of calibration and verification was required before the *ROSAT* All-Sky Survey (RASS) could commence. Thus, it was not until 6 weeks later, on July 11, 1990, that the first observations for the *RASS* were taken (see Table 2.1). The survey employed both the PSPC-C and PSPC-B to scan the entire sky in great circles of 2°-wide strips, while its pointing position was “roughly” perpendicular to the Earth-sun plane (Briel et al. 1996). This strategy resulted in typical exposure times of $\sim 400$ s over most of the sky, but very deep exposures were achieved near the ecliptic poles ($\sim 40,000$ s), where the scans overlapped (Voges et al. 1999). Unfortunately, due to a computer glitch, the operators lost
control of the satellite for approximately 15 hours after the end of its second
observation interval. Within that time the PSPC-C had accidentally scanned
across the sun, causing complete destruction of the detector and damaging the
WFC (Voges et al. 1999; Briel et al. 1996). Fortunately, PSPC-B was identical to
PSPC-C and it was used to finish the all-sky survey.

<table>
<thead>
<tr>
<th>Observation Intervals</th>
<th>ROSAT Days $^1$</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990 Jul 11 - 1990 Jul 16</td>
<td>41-45</td>
<td>PSPC-C</td>
</tr>
</tbody>
</table>

Table 2.1: The observation intervals of RASS (from Voges et al. 1999)
(1) ROSAT days are the days since launch on 1990 Jun 01.
(2) The detector PSPC-C was destroyed on Jan 25 1991, when it accidentally scanned
the Sun.

In totality there were 18,806 bright sources in the RASS Bright Source Catalog
(RASS BSC) and 105,924 sources in the RASS Faint Source Catalog (RASS FSC).
Together the RASS covered $\sim97\%$ of the sky for exposure times greater than 100
s (Voges et al. 1999, 2000).

2.3 Cross-Correlation of the Source Catalogs

As mentioned above, there are many similarities between the Einstein surveys
and the RASS, especially in their X-ray set up. Most importantly, the Einstein
IPC and the ROSAT PSPCs were most sensitive in the soft X-ray band (0.5-2
keV). However, ROSAT was about $2\times$ more sensitive than Einstein, and it had
a wider field-of-view and better spatial resolution in the central portion of the
field-of-view (see Table 2.2). These differences were not substantial, allowing the
source catalogs associated with each facility to be compared directly.
2. Experimental Design

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spatial Resolution</th>
<th>Field of View</th>
<th>Effective Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPC</td>
<td>1'</td>
<td>60' × 60'</td>
<td>100 cm²</td>
</tr>
<tr>
<td>PSPC</td>
<td>0.25' at 1 keV</td>
<td>2° dia.</td>
<td>240 cm² at 1 keV</td>
</tr>
</tbody>
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Table 2.2: Properties of the *Einstein* IPC and *ROSAT* PSPC instruments (see Giacconi et al. 1979; Briel et al. 1996).

Specifically, the position uncertainties for the *Einstein* and *RASS* sources are substantial and must be considered when attempting to identify true “matches,” i.e., detections of the same source in each catalog. Two different scenarios result when comparing the two X-ray catalogs: One in which the two source position uncertainties do not overlap sufficiently, resulting in a “chance coincidence,” and one in which the source position uncertainties do overlap, and a “true” match is found (Figure 2.2 left and right, respectively). In Figure 2.2, the pink circle represents the source position error of *RASS*, whereas the blue represents the source position error associated with the *Einstein*.

Figure 2.2: Two scenarios illustrating the results of a comparison between *Einstein* Two-Sigma Catalog and the *RASS*. The cataloged 1σ source position offsets are the same in each. Left: an uncorrelated result or a chance coincidence. Right: a correlated result or a “true match”.

The total number of matches in the Two-Sigma catalog and the *RASS* FSC
were plotted as a function of source position offset, $r$ (Moran et al. 1996b; Voges et al. 2000). As the source position offset increases, the number of genuine matches should decrease. Yet, with larger position offsets, there is a higher probability that a match involves two independent sources, which causes the number of correlations to increase again. The difficulty with this type of plot is that it doesn’t incorporate the source position errors, which, as shown in Figure 2.2, is important for assessing whether or not a match is genuine. Moreover, it is difficult to determine the relative numbers of genuine and chance coincidences at a given offset time when the number of matches vs. offset is plotted.

Two changes can be made to improve how the cross-correlation results are visualized. First, the number of chance coincidences per unit area should be constant. If the number of matches in a given offset bin is divided by the area of that bin, then a plot of this “source density” as a function of offset should be constant at large offsets where the chance coincidences dominate. The constant chance coincidence level can be confirmed by randomly shifting the positions of sources in one of the catalogs and reperforming the cross-correlation, which would simulate uncorrelated results (Moran et al. 1996b; Moran 2016).

Second, we can compute the normalized offset for each match, which represents the offset divided by the root-sum-squared of the Einstein IPC and RASS position errors:

$$\text{normalized offset} = \frac{r}{\sqrt{\sigma^2_{IPC} + \sigma^2_{RASS}}}.$$  \hspace{1cm} (2.1)

The normalized offset is more directly related to the probability that a match is genuine.

In combination, a plot of source density versus normalized offset allows us to
construct a sample of matches for which statistical reliability can be accurately accessed. As Figure 2.3 illustrates, the genuine match fraction as a function of normalized offset is clearly shown in this type of plot. For example, the first offset bin (normalized offset $< 0.2$) contains 143 matches, 95% of which are expected to be genuine. The seventh offset bin ($1.2 < \text{normalized offset} < 1.4$) contains 405 matches, but only 75% are genuine. Considering all matches with a normalized offset $< 1.4$ yields a sample of 3361 sources that has an overall reliability of 90%.

![Image of Figure 2.3](image)

**Figure 2.3:** *Einstein* IPC-RASS cross-correlation results (from Moran 2016). At each normalized offset bin (see Figure 2.1), the number of matches divided by the area of the bin is plotted. The (constant) chance coincidence level is indicated by the dotted line.

### 2.4 IPC Sources Undetected in the RASS

Considering only high-significance *Einstein* IPC sources ($> 3\sigma$), there are 5,252 X-ray sources that lack a counterpart in the *RASS*. In all likelihood, the majority of these occur because of the shallow exposures in the *RASS*, but some cases could be the result of extreme changes in luminosity, so we include these
2. Experimental Design

*Einstein* IPC-only sources in our search for dramatic variability.

### 2.5 Defining a Sample of Variable X-ray Sources

As noted above, the *Einstein* IPC and the *ROSAT* PSPC have different sensitivities. Thus, in order to search for variations in brightness, we must convert the observed count rates of the sources in the catalogs to energy flux. First, we adopt a model for the spectra of the X-ray sources. Then, combining the sensitivity functions of the two instruments with count rates observed in their respective band passes, we compute the fluxes for the two observations in a common energy range (0.5-2 keV).

“WebPIMMS” is an online tool developed by Koji Mukai that converts net count rates into X-ray fluxes. It uses the effective area as a function of the photon energy for several instruments, such as the *Einstein* IPC, *ROSAT* PSPC and HRI, along with a user supplied spectral model. For this research, we use a power law with a photon index of $\Gamma = 2.3$ (appropriate for the *RASS* sources; Boller et al. 1992) as the spectral model, and assume a value for the Galactic absorption column density of $N_H = 1.5 \times 10^{20} \text{ cm}^{-2}$ (the mean value at high Galactic latitudes). Thus, for *Einstein* IPC detections in the 0.16-3.5 keV range, WebPIMMS predicts a flux in the 0.5-2.0 keV band of $1.54 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ for a count rate of 1 ct s$^{-1}$. For *ROSAT* detections in the 0.1-2.4 keV band, WebPIMMS predicts fluxes (0.5-2.0 keV) of $4.38 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ and $1.84 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ for the PSPC and HRI count rates of 1 ct s$^{-1}$, respectively. These values represent conversion factors that can be used to compute the fluxes of the *Einstein* IPC and *RASS* sources.

\[\text{Mukai, K. 1993, Legacy 3, 21-31.}\]
Applying these conversion factors to the source matches, identified in the cross-correlation, we obtain a median ratio of the *Einstein* IPC and the *ROSAT* PSPC fluxes of 1.0 for our sample. But as Figure 2.4 indicates, a number of matches appear to display significant variability. The left plot shows the IPC/PSPC flux ratio as a function of *Einstein* IPC source significance for the entire set of matches. The right plot zooms into the range 2-3.3σ for the *Einstein* IPC detections, where the most variable sources are found. The error bars in this plot show that the apparent variability of many source is not statistically significant. However, despite the weakness of the *Einstein* IPC detections, large-amplitude variability is confirmed in a number of others.

Figure 2.4: The log ratio of the *Einstein* and *RASS* fluxes plotted against the *Einstein* source significance. The sources above the line decreased in flux, while the sources below the line increased in flux. The left image is the zoom out version of the right image (from Moran 2016). The fluxes were calculated, assuming a hydrogen column density of $\sim 4 \times 10^{20} \text{ cm}^{-2}$ and a power law of 1.

Figure 2.5, shows the fluxes of *Einstein* IPC sources that were not detected in the *RASS*. For these sources we have calculated upper limits for the *RASS* flux by assuming a count rate limit expected from 10 photons (barely detected) divided by the *RASS* exposure times at their sky locations (Voges et al. 1999). These count rate upper limits were then converted to upper limits in fluxes, using the
ROSAT PSPC conversion factor above, to get the minimum variability factors for these sources.

\[ \text{Figure 2.5: The log of the } \textit{Einstein} \text{ IPC flux plotted against the } \textit{Einstein} \text{ IPC source significance.} \]

Our sample of dramatically variable X-ray sources must have large variability amplitudes and statistically significant differences between the \textit{Einstein} IPC flux and the \textit{RASS} flux (or upper limit). Figure 2.6 shows a plot of IPC/RASS flux minimum ratio vs. significance of the IPC/RASS flux difference. Our final sample of variable sources consist of those with IPC/RASS or RASS/IPC ratios of at least $\sim 7$ (similar to the Changing-Look QSO, J0159+0033, discussed in §1.2.2), for which the flux difference exceeds $3.3\sigma$ significance. Represented by the 204 closed orange circles and blue open circles is total number of sources that meet this criteria.
2. Experimental Design

Figure 2.6: The log of the Einstein IPC and the RASS flux ratio plotted against the significance of their flux difference. Variability is most robust for those sources for which the difference between the Einstein IPC flux and the RASS flux limit exceeds $3.3\sigma$. The “true matches” that have varied by a factor of $>7$ are represented by orange closed circles. Einstein sources, detected above $3\sigma$ that were not detected in the RASS are represented by the blue open circles.

Figure 2.7 plots the celestial coordinates of these sources, overlaid on the RASS exposure map. The top plot shows sources that have brightened between $\sim1980$ and $\sim1990$. Only a handful of these sources are found across the sky. The bottom plot shows sources that have dimmed over the same $\sim10$ year span. The majority, 38, are found in the North Ecliptic Pole (NEP). This is because a shallow survey was performed with the Einstein IPC and where ROSAT had the most integration time. Thus, sources detected by Einstein must be bright. The depth of the RASS exposure time ensures that any source that varied dramatically can be identified with high confidence. The NEP sources also have the largest variability amplitude. For this reason, our sample focuses on this subset. Their basic properties are listed in Tables 2.3 and 2.4. The next chapter presents optical spectroscopy of the 10 AGNs from the NEP sources. Chapter 4 will then present their long-term X-ray light curves.
Figure 2.7: These image represents the exposure map for the RASS overlaid by X-ray variable sources. The lighter areas have the greatest integration time. The top map shows the locations of Einstein sources that gotten brighter, while the bottom map shows sources that have dimmed. The grey and orange dots represent Einstein sources detected in the RASS that have dimmed by factors ranging from 7 to 43, and the green and blue sources were not detected in the RASS–minimum variability factors ranging from $>8\times$ up to $>297\times$ (from Moran 2016).
Table 2.3: NEP *Einstein* IPC and *RASS* detected X-ray Sources

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### Table 2.4: NEP *Einstein* IPC-only X-ray Sources

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(1) RASS source name. (2) Minimum variability (calculated from *Einstein* IPC/upper limit of the RASS flux). (3) *Einstein* IPC source significance (sigma). (4) Net *Einstein* IPC source counts (1.25 arc minutes radius aperture). (5) *Einstein* IPC exposure time (s, in 1.25 arc minutes radius aperture). (6) RASS exposure time (s).
Chapter 3

Optical Spectra

To determine if any of the variable X-ray sources, detected by both Einstein and in the RASS or only by Einstein, are AGNs, optical spectra were obtained with the Palomar 5m Telescope in June 2017. Using optical images of each field from the Digitized Sky Survey and the MDM 1.3m telescope, two error circles were overlaid onto the images to represent the position errors of Einstein IPC and ROSAT PSPC sources. Potential optical counterparts were identified within and around the smallest error circles and labeled with a letter. Figure 3.1 shows two examples, one of both Einstein IPC and ROSAT PSPC, and the other of a Einstein IPC-only field.

Figure 3.1: Optical field for (left) both Einstein IPC sources and RASS and (right) Einstein IPC-only sources. The large green error circles represent Einstein IPC position error and the small yellow error circle the RASS position error, as described in §2.3. In the left image, object $A$ is the X-ray source optical counter part. In the right image, the counter part is object $B$. 
3. Classification of Optical Spectra

The set-up for the double spectrograph used a grating of 300/3900 and 316/7500 for the blue and red sides, respectively. The incoming light beam would be split, transmitting the red light and reflecting the blue light at 5500 Å (i.e., a D55 dichroic). Combined, the spectra have a total wavelength range of $\approx 4250$-$10,200$ Å. The exposure times for the optical sources range from 900 to 1800 seconds, depending on their brightness in the images. The optical spectra were reduced and analyzed following the standard procedure using the IRAF software\textsuperscript{1}. Then the blue and red spectra are combined in IRAF after they are reduced.

3.1.1 Active Galactic Nuclei

J1732+6748:
The optical spectrum for the source J1732+6748 is presented in Figure 3.2. The spectrum has a redshift of $z = 0.32$, thus, the broad emission lines, H\textbeta (4861 Å) and H\textalpha (6563 Å) are located at 6397 Å and 8637 Å, respectively. The shape of the H\textbeta and forbidden [O III] doublet emission lines are characteristic of a type 1 Seyfert galaxy. Moreover, around 6000 Å and 7000 Å are the distinguishable Fe II “humps” of a type 1 Seyfert galaxy.

3. Optical Spectra

**Figure 3.2:** Optical spectrum of the Seyfert 1 galaxy, J1732+6748.

**J1733+6749:**

The optical spectrum for the source J1733+6749, \( z = 3.58 \), is shown in Figure 3.3. Since the optical spectrum is very redshift, the most prominent feature is the Ly\( \alpha \) \( \lambda 1216 \) emission line detected at 5569 Å, followed by the C IV \( \lambda 1549 \) emission line at 7094 Å. These two characteristics are found in QSOs.

**Figure 3.3:** Optical spectrum of QSO, J1733+6749
J1733+6834:

The optical spectrum for J1733+6834, \( z = 0.29 \), is presented in Figure 3.4. The \( \text{H} \beta \) and \( \text{H} \alpha \) emission lines, at 6251 Å and 8440 Å, respectively, are narrow with Lorentzian profiles rather than Gaussian. The \( \text{H} \alpha \) emission line, in particular, has conspicuous Lorentzian wings (Sulentic et al. 2000; Véron-Cetty et al. 2001; Marziani et al. 2003; Laor 2006). This, along with the shape of the forbidden \([\text{O III}] \lambda \lambda 4959,5007\) lines at 6377 Å and 6439 Å, respectively, classifies this object as Narrow-line Seyfert 1 galaxy (Osterbrock & Pogge 1985), which are generally known to be variable X-ray sources (e.g., Boller et al. 1996). NLS1s are Seyfert galaxies with spectral characteristics of both type 1 and type 2 Seyfert galaxies. Their high-ionization and featureless spectra match Seyfert 1 galaxies, but its line widths and dispersion velocities match Seyfert 2 galaxies (Koski 1978; Cohen 1983; Osterbrock 1984; Cohen & Osterbrock 1981). NLS1s also share the \( \text{Fe II} \) characteristics from the Seyfert 1 galaxies. However they do appear to be exceptionally weak in this spectrum (Boroson & Green 1992).

Figure 3.4: Optical spectrum of the NLS1, J1733+6834
3. Optical Spectra

**J1755+6638:**

The optical spectrum for J1755+6638, at $z = 1.03$, is shown in Figure 3.5. The only resolvable feature in this spectrum is the broad Mg II $\lambda$2800 Å emission line detected at 5673 Å, a characteristic of QSOs.

![Figure 3.5: Optical spectrum of the QSO, J1755+6638](image)

**J1801+6624:**

The optical spectrum for J1801+6624, at $z = 1.26$, is presented in Figure 3.6. This spectrum shows a less noisy broad Mg II $\lambda$2800 Å emission line, located at 6328 Å. It also appears to show a weak [Ne V] $\lambda$3426 forbidden line at 7743 Å, near the stitching of the spectrum. Note the power-law slope of the continuum, which is also a characteristic of QSOs.
The optical spectrum for the X-ray source J1803+6529, $z = 0.40$, is shown in Figure 3.7. The spectrum has a narrow $\text{H}\beta$ emission line and strong [O III] $\lambda\lambda 4959, 5007$ emission lines at 6791 Å, 6928 Å, and 6995 Å, respectively, where the [O III] $\lambda 5007$ emission line is the strongest. The spectrum also features a narrow $\text{H}\alpha$ emission line located at 9169 Å, rendering this X-ray source a Seyfert 2 galaxy.
J1808+6744:

The optical spectrum for J1808+6744, $z = 1.63$, is presented in Figure 3.8. The only resolvable feature of this spectrum is the Mg II $\lambda 2800$ emission line located at 7361 Å, marking this a QSO.
3. Optical Spectra

**J1809+6620:**

The optical spectrum for the X-ray source J1809+6620, \( z = 0.63 \), is shown in Figure 3.9. The main features of the spectrum are the Mg II \( \lambda 2800 \) emission line at 4567 Å, the strong and broad H\( \beta \) emission line at 7928 Å, and the [O III] \( \lambda \lambda 4959, 5007 \) emission lines at 8094 Å and 8166 Å, respectively. The latter being the strongest. This spectrum also has an apparent power-law continuum slope, all characteristic of a QSO.

![Figure 3.9: Optical spectrum of the QSO, J1809+6620](image)

**J1814+6530:**

The optical spectrum for J1814+6530, \( z = 0.62 \), is presented in Figure 3.10. There is a broad H\( \beta \) emission line at 7060 Å, and a weaker [O III] \( \lambda 5007 \) emission line at 8106 Å. On the left side of the H\( \beta \) line are more Balmer emission lines: the H\( \delta \) \( \lambda 4101 \) at 6639 Å and the H\( \gamma \) \( \lambda 4340 \) at 7026 Å. These, along with the power-law continuum slope, are features of a QSO spectrum.
3. Optical Spectra

Figure 3.10: Optical spectrum of the QSO, J1814+6530

**J1828+6547:**

The optical spectrum for J1828+6547, $z = 0.68$, is shown in Figure 3.11. There is a Mg II $\lambda 2800$ emission line at 4696 Å, a forbidden [O II] $\lambda 3727$ emission line at 6250 Å, a forbidden [Ne III] $\lambda 3869$ at 6487 Å, a small (but broad) H$\delta$ emission line at 6877 Å, a broad H$\gamma$ emission line at 7278 Å, a broad H$\beta$ emission line at 8152 Å, and a [O III] doublet at 8316 Å and 8397 Å, respectively. With all of these components taken into account, it is most probable that this is a QSO, although, it may look like a class of Seyfert galaxy.
3.1.2 A dMe Star

Another interesting finding from the optical spectra was the discovery of a subclass of M-dwarfs called “dMe” (“e” for emission). DMe or flare stars, are especially known for having high stellar activity such as powerful X-ray emission, a lot of magnetic field activity. Though unrelated to the aim of this project, one of the variable sources in our sample, J1751+7035, is very interesting. The source was first observed on 28 May 1980, then again on 29 May 1980 with the Einstein IPC at exposure times of 375 seconds and 335 seconds, respectively. In 24 hours between the observations, the source disappeared. When it was observed, at an exposure time of 5280 seconds, nearly a decade later in the RASS it had dimmed by a factor of at least 297, meaning the source was not detected. No other X-ray observatory has detected it since. Figure 3.12 shows the optical spectra of J1751+7035 and Proxima Centauri\(^2\), another flare star of a similar spectral type.

(M5.5Ve and M5Ve, respectively).

Figure 3.12: Optical spectrum of J1751+7035 (from Palomar 5m Telescope) and Proxima Centauri (from the MUSCLE Program). The MUSCLES program studies the ultraviolet spectrum incident for exoplanets from their host M-dwarfs, to better model their atmospheres.

The flux density for both spectra were converted to luminosity density by multiplying the flux to the distance squared. To find the distance to J1751+7035, we use the distance modulus equation (1), where the apparent magnitude in the visible\(^3\) is about 20.54, and the absolute magnitude is assumed to be the same as Proxima Centauri (\(M_v = 15.60\) Benedict et al. 1999):

\[
m - M_v = 5 \log \left( \frac{d}{10 \text{pc}} \right). \tag{3.1}
\]

Therefore, the estimated distance to J1751+7035 is about 100 parsecs, whereas Proxima Centauri at about 1.3 parsecs from the Earth (ESA 1997). Note that the lines in the two spectra almost match, but Proxima Centauri is luminous. Another important note is that with a single spectrum taken of J1751+7035, it is unclear whether or not it was flaring or in its quiescent state. Based on its comparison to Proxima Centauri’s quiescent state, we assumed it was flaring. More spectra

\(^3\)Accounting for extinction between the earth and J1751+7035. \(A_v = 0.11\) (max)
could allow us to use its Ca II H&K lines to learn something about its magnetic field.

Many of the sources observed with the Palomar 5m Telescope were either unsuccessful, inconclusive, or not AGNs, as shown in this section. The next section will discuss the optical spectra properties of the 10 AGNs in our sample.

This next chapter will present and discuss the long-term X-ray light curves of 10 AGNs.
Chapter 4

The X-ray Light Curves

Most of the post-\textit{RASS} data are available as pointed observations from the \textit{ROSAT} PSPC and HRI instruments. The next couple of sections will describe each of the instruments’ design and the data analysis process.

4.1 \textbf{ROSAT PSPC}

Both of \textit{ROSAT}’s proportional counters, PSPC-B and PSPC-C, have four electrode wire grids filled with a gas mixture of 65\% argon, 20\% xenon and 15\% methane. Two of these, K1 and K2, are cathode grids that are perpendicular to each other, and the other two are anode grids; one (A1) is used in tandem with the cathodes to determine position of an event and the other (A2) is used as a anti-coincidence counter to reject background signal. The K1 and K2 gold-plated platinum iridium wires are 50 \textmu m in diameter and are spaced by 0.5mm. These cathode grids are made from strips of seven or eight tied wires and are attached to a preamplifier. The anodes A1 and A2 are almost identical except for the spacing of their gold-plated tungsten 10\mu m (diameter) wires; A1 and A2 are spaced by 1.5 mm and 2mm, respectively. At the edges of the anode grids there are guard wires that increase in diameter, to lower the electric field. Figure 4.1 shows a schematic cross-section of the \textit{ROSAT} PSPC (Briel et al. 1996).
4. The X-ray Light Curves

Figure 4.1: A cross-section diagram of the *ROSAT* PSPC (from Briel et al. 1996). The K1 and K2 cathodes and the A1 anode grids are used to determine event positions. The A2 anode is used as an anti-coincidence counter for rejecting background signals. Each grid is filled with a mixture of 65% argon, 20% xenon, an 15% methane.

Thus, an incoming X-ray photon would go through the 1μm window and knock off a photon-electron from the mixed gas. This electron, accelerated by high voltage, will then gain kinetic energy and collide with other atoms to create an electron cloud (a secondary electron cloud). The cloud then moves through the K1 grid to the A1 grid, increasing the electric field and causing the cloud to ionize more atoms. This process causes a charge pulse, proportional to the energy of the detected photon, at the anode and an induced signal (gain) at the cathodes, which are read by the preamplifiers. The digitized\(^1\) signal yields a reading of the energy and position of the events (Briel et al. 1996).

Figure 4.2 shows the thin plastic window support structure of the *ROSAT* PSPCs. Encircling the center is a rigid ring with a diameter of 20′, with eight

\(^1\)To digitized the signal, pulse shapers, peak detectors and analog-to-digital converters are used.
equally spaced “ribs” connecting the circle to the edge of the field-of-view at 60′.
Overlaid, are two tungsten wire meshes, one is 100 \( \mu m \) coarse wire mesh of 171″ spacing, and the other is a fine 25 \( \mu m \) wire mesh with 34.4″ spacing. This structure causes a shadow onto the data, which as discussed below is blurred following a conversion from detector coordinates to sky coordinates.

![Figure 4.2: The ROSAT PSPC schematic showing the window support structure (from Briel et al. 1996).](image)

Unlike the survey observation mode, where the telescope scanned the sky in great circles on a perpendicular direction to the Earth-Sun plane, the pointed observations used the wobble mode. Specifically for the \textit{ROSAT} PSPC, the telescope moved back and forth \( \pm 3′ \) every 400 seconds. This mode was implemented to avoid the shadowing caused by the coarse wire mesh of the window support structure (Briel et al. 1996). In Figure 4.3, the left image (in detector coordinates) shows this dither pattern as well as a clear view of the shadowing caused by the wire mesh, the ribs, and the ring. Of course, as is, such an image could not be used to conduct effective science. However, since each event had information on
the photon arrival time, its location in detector coordinates and where the satellite was in its dither pattern, a corrected image could be created in sky coordinates (right).

Another effect visible from the image above is the vignetting towards the edges of the field-of-view caused by the mirror assembly. With increasing off-axis angle (> 6′), the X-rays hit the primary mirror at shallower angles, which causes some to miss the secondary mirror, which reduces the effective area and the effective exposure times (Boese 2000). Since for our project, we consider the 0.5-2 keV range anything greater than 1 keV is susceptible to vignetting, which requires us to apply a correction (Briel et al. 1996). Vignetting can be corrected by making an exposure map for the data to determine the count rate as function of position in the image. Unfortunately, vignetting, and thus exposure maps, are energy-dependent, which means that an exposure map would need to be made for each energy band and for each observation of a source. In order to preserve the information about the photon energies, a different method of analysis must be used (see §4.2 below).
Figure 4.3: Two images from the same ROSAT PSPC event file. The image on the left, in detector coordinates, shows the original dither pattern of the telescope. Thus, the red and yellow sources show up as diagonal streaks as described in the text. The image on the right shows the corrected image, in sky coordinates, reveals several point sources, blurred wire mesh, ribs, and ring. Images in this format were used to perform aperture photometry.

An additional effect visible in Figure 4.3 (right) is the degradation of the point spread function (PSF) outside the ring (> 20'). The pattern is caused by curvature of the focal surface, whereas the ROSAT PSPC is flat. Hasinger et al. (1994) created a model for the off-axis angle and energy-dependent PSF that accounts for scattering due to the micro-roughness of the mirrors, blurring effect caused by the alignment of the mirror assembly, and the curved focal surface. Using this model for the PSF, Boese (2000) computed values of the cumulative PSF (or “encircled energy”)\(^2\), which is the fraction of counts from a point source included within an aperture of a certain radius. The cumulative PSF for different off-axis angles at 1 keV is plotted against the source “extraction radius” or aperture radius in Figure 4.4. We have used this analysis to determine aperture sizes for sources in our sample observed with the ROSAT PSPC.

Since most of the cumulative PSFs for on-axis and off-axis point sources of

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\(^2\)the PSF integrated radially and azimuthally
energies ranging from 0.1 to 2 keV converge at 92%, we adopted a value of 0.92 to set the aperture radius in our analysis. Using equations for the cumulative PSF from Boese (2000), we have computed a function to yield source apertures. Because the PSF degrades rapidly at large off-axis angles, our analysis only includes sources located within 45’ of the optical axis. A function has been fitted using a combination of a hyperbolic and parabolic models to determine the aperture radii as a function of off-axis angles (Figure 4.5). Given a source position, an aperture containing at least 92% of the counts is used to extract the source counts.

Lastly, the background annulus is determined by adding 40’ and 80’ to the aperture size for the inner and outer regions, respectively. The properly scaled counts in the annulus is then subtracted from the counts in the source aperture to get the net count rate of the source (§4.2). However, sometimes the source intersects the ring or rib of the PSPC window structure (as the source in the red circle in Figure 4.3). In other instances, there may be a bright source in the background annulus. In those instances, it is important to create a background region to reject the shadow or the bright source. Thus, the annulus regions for these point sources are constructed manually as explained in the next section.

Figure 4.4: Cumulative point spread function source off-axis angle and aperture size for ROSAT PSPC at 1 keV (from Boese 2000). 0.92 or 92% is the PSF value adopted to maximize the number of counts within an aperture for different off-axis angles and energies.
4. The X-ray Light Curves

4.2 ROSAT PSPC Data Analysis

The ROSAT pointed observations are stored as events files in standard FITS format. Each file contains information such as the sky coordinates, the original detector coordinates, the arrival time, and the photon energy of each event. Using the “xselect” data analysis software from “ftools”\(^3\), an image can be made from an event file with specifications of spatial binning and energy bands.

The image can then be opened by SAOImage DS9 to perform aperture photometry with the apertures calculated from Figure 4.5. When necessary, the aperture and annulus sizes were altered to exclude any nearby source and the rings and ribs of the ROSAT PSPC. The spectra were extracted from both the source and the

background regions, which can be fitted by a model (like a power-law) in “xspec” to get a flux. However, before the spectra can be evaluated, xspec needs information about the detector response matrix or redistribution matrix file (RMF) and ancillary response file (ARF), which, for the *ROSAT* PSPC, is created by “pcarf”.

The response matrices, i.e., the 256 PI (pulse invariant) channel detector redistribution matrices, are a 2-dimensional arrays of energy vs. channel values that give the probability of an incoming photon causing an event in within a certain PI channel. PI channels are integers calculated from the PHA (pulse height amplitude) channel. Thus, with the RMF we can get information about the energy resolution of the detector (Turner 2011). However, unlike the PSPC-C, which was destroyed in 1991 Jan 25, the PSPC-B has two different response matrices due to the rate-gain effect (the saturated gain) caused by the electron cloud created in the PSPC gas design. Different response matrices must be used for observations made before and after 1991 Oct 14 (Turner 2011; Briel et al. 1996).

Furthermore, we needed to create an ARF for each observation to correct for several effects such as the wobbling of the detector, the vignetting of the mirrors, and the shadow of window structure; it takes form of a 1-dimensional matrix. Thus, the ARF is the physical spectrum or the effective area as a function of energy (Turner 2011). Once the files are applied to the spectrum created by the previous step, we further edit the spectra by ignoring data associated with channels outside the useful energy range (grouping with the ftool “grappha”) (Turner 2011).

Finally, we read the data into xspec, which reports a net count rate and a standard deviation. From the net count rate, there are two ways to calculate the flux. Xspec is capable of fitting spectral models to the data, with a given hydrogen column density to measure a flux. However, accurate spectral fitting
is not possible for weakly detected sources. Therefore, as mentioned in §2.5, this research project uses the online tool WebPIMMs to calculate the flux from the corrected count rate.

4.3 ROSAT HRI

In comparison to the Einstein IPC and the ROSAT PSPC, the ROSAT High Resolution Imager (HRI) has a smaller field-of-view and effective area, but better spatial resolution (Table 4.2). These differences can be attributed to the design of the ROSAT HRI.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spatial Resolution</th>
<th>Field-Of-View</th>
<th>Effective Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPC</td>
<td>1′</td>
<td>60′ × 60′</td>
<td>100 cm²</td>
</tr>
<tr>
<td>PSPC</td>
<td>0.25′ at 1 keV</td>
<td>2° dia.</td>
<td>240 cm² at 1 keV</td>
</tr>
<tr>
<td>HRI</td>
<td>1.7′ (FWHM)</td>
<td>20′ × 20′ (usable)</td>
<td>83.2 cm² at 1 keV</td>
</tr>
</tbody>
</table>

Table 4.1: Different properties of the Einstein IPC to the ROSAT PSPC and HRI detectors (see Giacconi et al. 1979; Briel et al. 1996).

Unlike the ROSAT PSPC, the ROSAT HRI is composed of two cascaded microchannel plate detectors (MCPs). Each channel or glass tube is coated with a photo-resistor, Cesium iodide. When an X-ray photon hits the material at an angle, it knocks off a photo-electron that is then accelerated by an applied voltage. As the accelerated electron cascades, it knocks off electrons from other atoms, resulting in an electron cloud. The detector then reads out an amplified signal, just as the ROSAT PSPC does. However, the process described in §4.1 is more linear in the PSPC than in the HRI. That is, for the PSPC the size of the charge cloud is more closely related to the energy of the original X-ray photon. However, as mentioned before the HRI has better spatial resolution.

Furthermore, like the PSPC, off-axis HRI sources were affected by vignetting,
degradation of the PSF, etc. Thus, we were able to use the cumulative PSF (from Boese 2000) for the *ROSAT* HRI to create a function that indicates off-axis position for different values of aperture radius (Figure 4.6). The cumulative HRI PSF is noticeably different than the *ROSAT* PSPC (Figure 4.4), each curve producing different patterns. While the *ROSAT* PSPC energies seem to converge at 0.92, the energies for the HRI converge at 0.85.

![Cumulative point spread function source off-axis angle and aperture size for ROSAT PSPC at 1 keV (from Boese 2000). 0.85 or 85% is the PSF value adopted to maximize the number of counts within an aperture for different off-axis angles and energies.](image)

As before, the points at 0.85 were plotted against off-axis angles ($\leq 20'$) but fitted with a combination of a linear function and power law instead (Figure 4.7). However, aside from the small differences in the equations for the aperture radius function, the process of setting the size of the background annulus region for photometry remains the same. Because the HRI has no energy resolution, straightforward aperture photometry is used to obtain accurate source soft X-ray fluxes and upper limits.

---


5 Note that the off-axis angles stop at 20' because the PSF changes abruptly for angles greater than 20'.
4.4 X-ray Light Curves

Using soft X-ray fluxes of sources observed with the *Einstein* IPC, the *RASS*, and pointed observations with *ROSAT*, we have constructed long-term X-ray light curves for most of the variable AGNs identified in our sample. The light curves for 9 objects are shown in Figures 4.8-4.16. The tenth objects was only observed with the *Einstein* IPC and the *RASS*. *PSPC* sources detected above 2.5σ were considered detections, and their fluxes were calculated using WebPIMMs. For non-detected sources, the upper limits were calculated as 3× the uncertainty in the measured background. The fluxes and upper limits were then normalized by the measured *Einstein* IPC flux. To find the errors, the following two equations
were used for the IPC\footnote{the net IPC source uses a 1.25$'$ radius aperture.} and the RASS\footnote{The standard deviation is calculated by xspec}, respectively:

\[
\sigma_{IPC} = \sqrt{\frac{\text{net source counts}}{\text{exposure time}}} \times \frac{\text{conversion factor}}{\text{IPC flux}}
\]

\[
\sigma_{ROSAT} = \frac{\text{count rate std. dev.} \times \text{conversion factor}}{\text{IPC flux}}
\]

The remainder of this section presents the long-term X-ray light curves and maximum variability properties of the AGNs in our sample.

**J1732+6748:**

The long-term X-ray light curve for the source J1732+6748 is presented in Figure 4.8, which plots the 0.5-2 keV flux (normalized to that observed with the *Einstein IPC*) against the Modified Julian Date (MJD-44000). Aside from the *Einstein IPC* and *RASS* points, there is one PSPC detection at MJD-44000 = 5410 with an exposure time of 6427 seconds, as well as three PSPC upper limits from images with lower exposure times. Note that, as the exposure time decreases the upper limit become less constraining. For example, the upper limit at MJD-44000 = 6482 had an exposure time of 1139 seconds, while the second upper limit MJD-44000 = 5503, had an exposure time of 4129 seconds. Nevertheless, the PSPC data demonstrate that the X-ray source never returned to its *Einstein*-era brightness. Its observed variability factor is 10.5.
4. The X-ray Light Curves

Figure 4.8: X-ray light curve for J1732+6748. The *Einstein* IPC and *RASS* observations are on MJD-44000 389 and 4281, respectively. The black points represent detections while the gray arrows are upper limits for non-detections from the *ROSAT* PSPC pointed observations.

**J1733+6749:**

The long-term X-ray light curve for the X-ray source, J1733+6749, is presented in Figure 4.9. This source was not detected at all after the *Einstein* IPC observation despite a *RASS* exposure time of 6298 seconds. Furthermore, all of its upper limits have of the exposure times between 1000-6000 seconds. Thus, the source has not returned to its *Einstein*-era brightness and its minimum variability factor is 75.8.
4. THE X-RAY LIGHT CURVES

Figure 4.9: X-ray light curve for J1733+6749. The symbols are the same as mentioned in Figure 4.8.

**J1733+6834:**

The long-term X-ray light curve for J1733+6834 is shown in Figure 4.10. Besides the *Einstein* IPC and the *RASS* observations, it has one weak detection at MJD-44000 = 6482 and four upper limits. However, it is important to note that the upper limits are maybe a result of the rings blocking or muting the source signal. Moreover, it was not clear if the source was obscured by the PSPC ring structure for the detection, which would render that detection inconclusive. Nevertheless, the source remains dimmer than in the *Einstein* observation, and the variability factor is 9.0.
4. The X-ray Light Curves

Figure 4.10: X-ray light curve J1733+6834. The symbols are the same as mentioned in Figure 4.8.

**J1755+6738:**

The long-term light curve for J1755+6738 is presented in Figure 4.11. Similar to J1801+6624, it also has many upper limits from exposure times lower than 3000 seconds. This source also has three observations after the RASS, which shows the source decreased in brightness before returning to its MJD-44000 = 4064 brightness. However, in the observation on MJD-44000 = 4470, the background annulus, not the source aperture, was corrected for the PSPC ring. Nevertheless, this source also did not return to its *Einstein*-era brightness. Its variability factor is 16.1.
4. The X-ray Light Curves

Figure 4.11: X-ray light curve J1755+6638. The symbols are the same as mentioned in Figure 4.8.

J1801+6624:

The X-ray long-term light curve for J1801+6624 is shown in Figure 4.12. Aside from its *Einstein* IPC and *RASS* points, it has three detections and many upper limits. Although most of its upper limits were of exposure times less than 6000 seconds, the one located at MJD-44000 = 4470 had an exposure time of 41204 seconds, which is comparable to the three other detections. However, it is important to note that, in that particular observation, the source is near the shadow of the *ROSAT* PSPC ring. Nevertheless, J1801+6624 has not returned to its original *Einstein* brightness, and it seems to fade as the exposure time decreases. Its maximum variability factor remains at 43.6.
4. The X-ray Light Curves

Figure 4.12: X-ray light curve for J1801+6624. The symbols are the same as mentioned in Figure 4.8.

**J1803+6529:**

The long-term X-ray light curve for the source J1803+6529 is shown in Figure 4.13. Other than the *Einstein* IPC and *RASS* points, it has seven upper limits of exposure times less than 5000 seconds. Nevertheless, the source has not returned to its *Einstein*-era brightness; its variability factor\(^8\) is 16.1.

\(^8\)Calculated by dividing the flux or upper limit by the *Einstein*
4. The X-ray Light Curves

Figure 4.13: X-ray light curve J1803+6529. The symbols are the same as mentioned in Figure 4.8.

**J1808+6744:**

The long-term X-ray light curve for J1808+6744 is shown in Figure 4.14. Aside from it *Einstein* IPC and *RASS* points, it has one pointed observation taken before the *RASS* data point. The *RASS* data point has a much larger exposure time of 11400 seconds, so it better constrains the post-*Einstein* brightness of this source. As the exposure time decreases, the source seems to fade. Its variability factor is 15.2.
4. The X-ray Light Curves

Figure 4.14: X-ray light curve J1808+6744. The symbols are the same as mentioned in Figure 4.8.

J1809+6620:

The X-ray long-term light curve for J1809+6620 (Figure 4.15) has four ROSAT PSPC detections and nine upper limits. The upper limit at MJD-44000 = 4370 has the lowest exposure time of only 102 seconds, while the other eight overlap with the three detections at MJD-44000 ≈ 4700. The last observation (detection) of this source at MJD-44000 = 4726, with an exposure time of 3048 seconds, agrees with the normalized RASS flux at MJD-44000 = 4281, which corresponds to an exposure time of 19,461 seconds. However, the flux seems to pop up prior to this. Nevertheless, it stayed below its Einstein IPC flux. Its variability factor is 16.1.
4. THE X-RAY LIGHT CURVES

Figure 4.15: X-ray light curve J1809+6620. The symbols are the same as mentioned in Figure 4.8.

**J1814+6530:**

The long-term X-ray light curve for source J1814+6530 is presented in Figure 4.16. Aside from the *Einstein* IPC and *RASS* points, this source has one upper limit of about 2000 seconds exposure time, which is low in comparison to the *RASS* exposure time of 9800 seconds. Its variability factor is 7.5.
4. The X-ray Light Curves

**Figure 4.16:** X-ray light curve for J1814+6530. The symbols are the same as mentioned in Figure 4.8.

**J1828+6547:**

This source did not have data associated with post-\textit{RASS} pointed observations. The variability factor based on the \textit{Einstein} IPC and \textit{RASS} detections is 9.3.

The individual results from the long-term X-ray light curves are summarized in Table 2.4. The name of the source is accompanied by its redshift (calculated from the optical spectra), its maximum luminosity in ergs s\(^{-1}\) (calculated from \textit{Einstein} IPC flux, assuming a Hubble constant of 73 km s\(^{-1}\) Mpc\(^{-1}\), and a flat universe with \(\Omega_m = 0.27\) and \(\Omega_\Lambda = 0.73\), its variability factor (calculated from \textit{Einstein} IPC flux divided by minimum the \textit{ROSAT} PSPC flux or upper limit, and its optical classification (from §3).
### Table 4.2: The results from the optical spectra and X-ray light curves for the 10 X-ray sources.

<table>
<thead>
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<td>1.73E44</td>
<td>7.5</td>
<td>QSO</td>
</tr>
<tr>
<td>J1828+6547</td>
<td>$z = 0.68$</td>
<td>4.20E44</td>
<td>9.3</td>
<td>QSO</td>
</tr>
</tbody>
</table>

Chapter 5 will delve deeper into these results by comparing the X-ray light curves and the optical spectra. The following questions will be discussed: What do the spectra and X-ray light curves say about these sources? Did any of the sources change their spectral classifications? What caused the dramatic changes in luminosity? Is it possible that some of the AGNs have brightened recently? And lastly, we will discuss the future of this project.
In the previous chapter, we concluded that none of the 10 AGNs from the NEP returned to its previous *Einstein*-era brightness. Seven out of the 10 AGNs in our sample are QSOs that dimmed dramatically by a range of factors (7.5-75.8), to more than similar to the soft X-ray variability factors of \( \sim 7.2 \) for J0159+0033 and \( \sim 100 \) for the optical continuum of Mrk 590, respectively (Denney et al. 2014; LaMassa et al. 2015). However, unlike Mrk 590 and J0159+0033, these QSOs did not transition spectroscopically to a different type of AGN. Although, less luminous, they remain broad-line AGNs optically. Only one of our objects is a CLAGN candidate. The galaxy starlight dominated optical spectrum of J1803+6529 contained narrow emissions lines, typical of a Seyfert 2 galaxy. However, in its *Einstein*-era it had a very bright (0.5-2 keV) X-ray luminosity, which was inconsistent with its Seyfert 2 classification. The next section will further discuss the interesting results.

5.1 Luminosity Dependence

As mentioned in §1.2.1, Mrk 590 is a 1.9 Seyfert galaxy that dimmed dramatically over a period of 40 years. Its soft (0.1-2.4 keV) X-ray luminosity decreased
from $4.38 \times 10^{46}$ ergs s$^{-1}$ to $3.13 \times 10^{45}$ ergs s$^{-1}$ in a single decade (1991-2004), values that are consistent with the Seyfert 1 galaxy classification (Denney et al. 2014). However, the object transitioned again to a type 1.9 Seyfert galaxy, depicted by the decrease in its recent (0.2-10 keV) X-ray luminosity to one of a type 1.9 Seyfert galaxy. Likewise, the (2-10 keV) X-ray luminosity for J0159+0033 shows the source dimming from a QSO ($8.33 \times 10^{43}$ ergs s$^{-1}$) to a type 1.9 Seyfert galaxy ($1.17 \times 10^{43}$ ergs s$^{-1}$), which is also consistent with its reclassification (LaMassa et al. 2015).

From the X-ray sources in the EMSS, Stocke et al. (1991) constrained the soft X-ray luminosity for Seyfert 1 galaxies and QSOs to a range from $L_x = 10^{43} - 10^{47}$ ergs s$^{-1}$, and for Seyfert 2 galaxy it to a range from $L_x = 10^{41} - 10^{43}$ ergs s$^{-1}$. The luminosity for our QSOs decreased by a lot, but still remained above the value expected from type 2 AGNs, retaining its type 1 classification. The CLQSO, J0159+0033, almost crosses the luminosity boundary at $10^{43}$ ergs s$^{-1}$, which agrees with its type 1.9 classification since type 1.9 Seyfert galaxies still have a weak but broad H$\alpha$ emission line component.

Figure 5.1 shows a plot of the soft (0.5-2 keV) X-ray luminosity ranges for all 10 our AGNs. The bars at the end of each range represents the maximum luminosity calculated from the *Einstein* IPC observations, and the minimum luminosity calculated from either the *RASS* observations or *ROSAT* PSPC pointed observations. The red line represents the soft X-ray luminosity boundary from Stocke et al. (1991), and the red shaded area shows the range of X-ray luminosity for Seyfert 2 galaxies. Although, the X-ray luminosity for the QSOs in our sample varied by a lot, their spectral type is still one of type 1 AGN. These QSOs are very luminous in comparison to J0159+0033, thus they would need to vary by factors greater than $\sim 20$ (or 100 for J1733+6749) to cross the boundary. Nevertheless,
the remainder of the section will take a closer look at three objects that crossed the $10^{43}$ ergs s$^{-1}$ boundary.

**Figure 5.1:** Maximum and minimum luminosity of the 10 AGNs. The maximum luminosity is from the *Einstein* IPC, whereas the minimum luminosity is from either the *RASS* or the *ROSAT* PSPC observations. The gray bar represents the most recent X-ray luminosity calculated from (only) the detected *ROSAT* PSPC point observations. The gray arrow on J1733+6748 represents the unknown current value of its X-ray luminosity, while the black bar in between represents the upper limit value from its *RASS* observation. The red line represents the Seyfert galaxy X-ray luminosity boundary, where the sources located to the left shaded region are Narrow-line Seyfert 1 or Seyfert 2 galaxies and the sources to the right are either Seyfert 1 galaxies or QSOs.

**J1732+6748:**

X-ray source, J1732+6748, was classified as a Seyfert 1 galaxy in §3.1.1 due to its Fe II humps and broad Balmer lines. In Figure 5.1, we noticed that its *Einstein* IPC (0.5-2.5 keV) X-ray luminosity is consistent with those of Seyfert 1 galaxies,
5. X-ray Variability and the Changing-Look Phenomenon

however, its \textit{RASS} luminosity seems to have crossed $10^{43}$ ergs s$^{-1}$, which doesn’t seem to fit our X-ray luminosity-based picture. However, when we consider the most current X-ray luminosity (the gray bar), we notice that, post-\textit{RASS}, this source returned to a typical Seyfert 1 galaxy X-ray brightness. It may correctly have a higher X-ray luminosity than in the \textit{RASS}, which would agree with its BLAGN classification.

\textbf{J1733+6834:}

X-ray source, J733+6834, was classified as a NLS1 due to its narrow Balmer Lorentzian profiles and Lorentzian wings on H$\alpha$. Note that it also crosses the luminosity boundary, but its current soft (0.5-2 keV) luminosity remains really close to the actually boundary line. Even so, its lower X-ray luminosity is still within the range expected for NLS1s (Moran et al. 1996a). Furthermore, Boller et al. (1996) notes NLS1s have dramatic short-term (minutes to hours) high-amplitude X-ray variability, which could be seen in its light curve (Figure 4.10)$^1$. Thus, this constitutes a “false-positive” for our survey.

\textbf{J1803+6529:}

X-ray source, J1803+6529, was classified as a Seyfert 2 galaxy due to its lack of broad Balmer lines and the fact that its continuum is dominated by host-galaxy starlight. Unlike the other two X-ray sources, this source is an excellent CLAGN candidate. Its \textit{Einstein} IPC X-ray luminosity started off in the Seyfert 1 galaxy range, but it decreased below that boundary to $L_x = 4.0 \times 10^{42}$ post-\textit{RASS}, which consistent with its current type 2 optical appearance.

Thus, all of the optical spectra are consistent with an X-ray luminosity dependence-picture, whereby Changing-Look spectra are only expected in dramatically vari-

\footnote{assuming the results are accurate}
able sources that transition to a sufficiently low X-ray luminosity. Present-epoch X-ray detections of these sources could completely confirm this picture.

5.2 Future Work

The future work could be summarized into four goals: The first is to complete the X-ray long-term light curves for the handful of these AGNs with achieved X-ray data from *Chandra*, *ASCA*, and *Swift*. The second is to try and find more CLAGNs using different permutations of source catalogs from different X-ray observatories, such as cross-correlating *Einstein* and *Chandra* or *Einstein* and *XMM-Newton* catalogs, like we did with the *Einstein* Two-Sigma catalog and the *RASS*. This could give arise to new possible Broad-line AGNs or CLAGNs that not have yet been studied. The third goal is to search through SDSS to find archived optical data to create optical long-term light curves for direct comparison to the X-ray light curves discussed in Chapter 4. The final goal is to take modern X-ray data and optical follow-up. This would provide a full picture of the optical and X-ray histories (and current standings) of these objects, which ultimately is needed to explore whether the changes in luminosity reflects the changes in their accretion states.
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