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A STUDY OF X-RAY POINT SOURCES IN ELLIPTICAL GALAXIES

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ABSTRACT
X-ray point sources in elliptical galaxies have attracted significant attention in recent years due to their dynamic nature and potential to unveil crucial insights into the astrophysical processes occurring within these enigmatic galactic structures. This abstract summarizes the current state of variability studies focused on X-ray point sources within elliptical galaxies, shedding light on the diverse phenomena and mechanisms that contribute to the temporal variations observed in these sources. The investigation of X-ray point source variability in elliptical galaxies has been driven by the continuous advancements in X-ray observatories, offering unprecedented sensitivity and temporal resolution. We discuss various methodologies and statistical approaches employed to analyze the light curves of these point sources, including time-series analysis techniques such as power spectral density estimation, autocorrelation, and Bayesian modeling.

KEYWORDS: X-ray point sources, elliptical galaxies, dynamic nature, Bayesian modeling

INTRODUCTION

Su- pernova Type Ia (Wang et al., 2007), abbreviated SN Ia, is a thermonuclear explosion that occurs when a carbon-oxygen white dwarf approaches the Chandrasekhar limit as a result of mass transfer from a donor or a merger. Being the brightest class of SN, and lacking hydrogen and helium in their early spectra, these events are distinct from the other main class of supernovae, the core-collapse type (CC).1

In addition, around optical maximum, they show lines of intermediate-mass elements including calcium, silicon, oxygen, and magnesium, and beginning about three weeks following optical maximum, they show lines of iron-peak elements, principally Fe II (Wheeler & Benetti, 2002).

Since these objects have been used as standard candles (e.g. Schmidt et al., 1998), they have been the subject of intensive research in order to better understand how the CDM paradigm calculates fundamental cosmological parameters like the density of matter and the cosmological constant.

There are two prominent hypotheses for the origin of SN Ia: the single degenerate (SD) channel, in which the progenitor is an interacting binary -star- system, and the multiple progenitor channel. The main, with its greater mass, develops to a white dwarf more quickly, whereas the secondary, with its greater ability to transfer mass, does so later in its stellar history.

The secondary star is either on the main sequence, a subgiant, or a red giant, and this is the most common scenario. The amount of mass transferred would be sufficient to surpass the Chandrasekhar mass (Mch) limit of 1.4MS, where S denotes the solar value. When two white dwarfs lose angular momentum and energy owing to the emission of gravitational radiation,

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they merge into a single object called a double degenerate (DD) channel (Gilfanov & Bogd'an, 2010). This happens during the likely ejection of a common envelope (hereinafter CE).

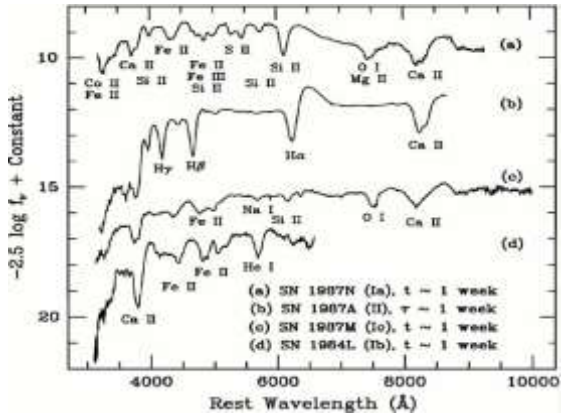

Figure 1 Spectra of SNe; we clearly see that in SN Ia dominate the intermediate-mass elements, while hydrogen and helium are lacking. From Filippenko (1997).

FORMALISM

The vector space -by Dirac- ket space has all the qualities of a Hilbert space, therefore let |A be a vector describing a specific state of a microscopic system1. The superposition principle holds, meaning that each state |A| is the superposition of two or more other states, and may be expressed in terms of the normalized basis |i|..|N| of the ket space

$$|A\rangle = \sum_{i..N} \alpha_i |i\rangle$$

where i is a complex number and i can be anything.

It is possible to see the bra associated with each ket as a special example of a linear functional F on |A|.

$$\begin{aligned} \langle F| &= \sum_{j..N} \beta_j^* \langle i| \\ \rightarrow \langle F|A\rangle &= \sum_{i..N} \sum_{j..N} \beta_j^* \alpha_i \underbrace{\langle j|i\rangle}_{\delta_{ij}} \\ &= \sum_{i..N} \beta_i^* \alpha_i \\ &= \sum_{i..N} (\beta_i \alpha_i^*)^* = \left(\sum_{i..N} \beta_i \alpha_i^* \right)^* \\ &= \langle A|F\rangle^* \end{aligned}$$

The Kronecker delta may be written as where ij = 1 if i = j and 0 otherwise. The last equation defines inner product, yielding a complex number in concept. The inner product is always real and equal to the norm of |A|, therefore it follows that if F A, then F A. The fact that the outer product of B| and |A, |AB|, corresponds to a linear operator is noteworthy.

We now introduce the idea of a linear operator X which, when applied to the kets |A, |B, yields still another ket set. In addition to not commuting with another operator Y (XY /=

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YX), one of the features of X is that it is associative on thekets4. The null operator X|A = |0| and the identity X|A = |A| are two such examples. The presence of an operator X owing to DC, where X|A A|X, should also be obvious

$$\langle B|X\hat{}\dagger|A\rangle = \langle A|X\hat{}|B\rangle*$$

potential for simple confirmation. The term "adjoint operator of X" is often used to refer to X. An operator is said to be Hermitian if and only if it is equivalent to its adjoint. Therefore, if operates on eigenkets |′, it follows that

$$\hat{\eta}|\eta'\rangle = \eta'|\eta'\rangle$$

with η′ being what's termed an eigenvalue, a real number. Hermitian operators have eigenvalues that are always real5 and eigenstates that are orthogonal (orthonormal after normalization).

Any Hermitian operator may be interpreted as a measurable observable of the system in a state |′. How likely is it, then, that the system will go from its initial state |A to a later state |′? Since |A is a linear combination of the components of the basis, satisfying |η | = 1 (sum over all states ′), and P (η′) is a positive integer, this probability is directly connected to |A|′η |2. To be sure

$$P(\eta') = \frac{|\langle A|\eta'\rangle|^2}{\sum_{\eta'} |\langle A|\eta'\rangle|^2}.$$

Now that we know how often it is for a system to "jump" from one state to another, we can rapidly move on to demonstrating some of the more interesting (and readily verifiable) aspects of the quantum mechanics universe.

1. Given an ensemble of systems in an initial (normalized) state |A, the expected value of any observable is = A||A.
2. Definitions such as dη′ |η′ ⟩⟨η′ | = 1, ⟨η′ |η′′ ⟩ = δ(η′ − η′′) (where Dirac delta) are generalized to a continuous spectrum in the second definition.
3. The notation for the commutation of two operators is [X, Y] = XY YX. If two operators commute, then both of them may be measured at the same time.
4. Analogous to Hamiltonian mechanics, if a system can be describe by the (generalized) coordinates x1..xi, xj (position) and p1..pi, pj (momentum), the relations of commutation of their corresponding operators x^1, .., x^i, x^j and p^1, .., p^i, p^j are written as [x^i, x^j] = 0, [p^i, p^j] = 0 and [x^i, p^j] = ikδij (unlike the classical result ≡ 0), with i = √−1 and the reduced Planck constant k.
5. The amount (x0 |A is a function of the position x′ and is known as the (position-space) wave function A(x′) in the continuous formalism, given a position operator x with eigenvalues x′ and eigen- kets |x′. The p operator is no different in this regard. This establishes the Fourier transforms of the wave functions in position space and momentum space.
6. In the continuous-functional paradigm, it is easy to prove that the x's and p's of an operator may be expressed as the derivative of one another, x' = ik d and p'x = ik d.

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Position-space representation (i.e. projection into x space), also known as the Schro dinger representation, will be used throughout this thesis.

7. It is possible to derive Heisenberg's uncertainty principle as follows: xpx k.

Schrodinger Equation

System has been expressed in terms of position and momentum at a fixed instant (time) t0, which is the moment of the measurement that defines the probability at any time t > t0 if the system stays unperturbed in the interval t = t t0. However, the state itself may evolve with time even if the likelihood to "jump" to it remains constant. To illustrate this, think of a system in an initial state at time zero (t0) that develops over a period of time t (|At0 and |At). The (time evolution) operator T describes how this state will change over time.

$$T \to |A_t\rangle = T|A_{t_0}\rangle$$

That satisfies

$$\mathrm{i}\hbar\frac{dT}{dt} = \hat{H}(t)T$$

Where H(t) is the system's Hamiltonian operator, and the system's total energy is measured in terms of its eigenvalues. The solution to the differential equation 2.5 looks like this:

$$T(t, t_0) = \exp\left(\frac{-\mathrm{i}}{\hbar}\int_{t_0}^{t}\hat{H}(t')dt'\right).$$

In its most basic form, the famous Schrodinger equation may be written as Equation 2.5. Consider a mass-m, one-dimensional particle whose location x (x operator) and momentum px (px operator) are expressed in terms of its potential V (x, t). H = px2 + V (x, t) is the formula for the Hamiltonian operator, thus

$$\mathrm{i}\hbar\frac{dT}{dt} = \hat{H}(t)T$$
$$\to \mathrm{i}\hbar\frac{dT|A_{t_0}\rangle}{dt} = \hat{H}(t)T|A_{t_0}\rangle.$$

The final equation follows from the definition of operator T (Equation).

$$\to \mathrm{i}\hbar\frac{d|A_t\rangle}{dt} = \hat{H}(t)|A_t\rangle.$$

Schrodinger's representation in position space.

$$\to \mathrm{i}\hbar\frac{\partial\langle x|A_t\rangle}{\partial t} = \hat{H}(t)\langle x|A_t\rangle$$

and by definition of ΨA(x) ≡ Ψ(x, t)

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$$\Rightarrow \mathrm{i}\hbar\frac{\partial\Psi(x,t)}{\partial t} = \hat{H}(t)\Psi(x,t).$$

Assuming a three-dimensional space, it is possible to prove, using H(t), that the corresponding equation is

$$\Rightarrow \mathrm{i}\hbar\frac{\partial\Psi(\mathbf{x},t)}{\partial t} = \left(\frac{-\hbar^2}{2m}\right)\boldsymbol{\nabla}^2\Psi(\mathbf{x},t) + V(\mathbf{x},t)\Psi(\mathbf{x},t)$$

with e.g. x = (x, y, z) and ∇ = $(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z})$. The overarching equation in quantum physics is known as the time-dependent Schrodinger equation.

Orbital Angular Momentum

Orbital angular momentum operator L = (Lx, Ly, Lz) in quantum mechanics may be represented in the same way as in classical mechanics by using the equation S.4 for position x = (x, y, z) and momentum p = (px, py, pz) operators and L = x p.

$$\begin{aligned}
\hat{L}_x &= \hat{y}\hat{p}_z - \hat{z}\hat{p}_y \\
\hat{L}_y &= \hat{z}\hat{p}_x - \hat{x}\hat{p}_z \\
\hat{L}_z &= \hat{x}\hat{p}_y - \hat{y}\hat{p}_x \\
\Rightarrow &\begin{cases}
[\hat{L}_x, \hat{L}_y] = \mathrm{i}\hbar\hat{L}_z \\
[\hat{L}_y, \hat{L}_z] = \mathrm{i}\hbar\hat{L}_x \\
[\hat{L}_z, \hat{L}_y] = \mathrm{i}\hbar\hat{L}_y \\
\quad\vdots
\end{cases}
\end{aligned}$$

It is evident that Lx, Ly, and Lz do not commute, hence it is impossible to measure them all simultaneously. With Lz as the observable and the operator L2 defined as L2 + L2 + L2, it is straightforward to demonstrate that

$$[\hat{L}^2, \hat{L}_z] = 0.$$

Therefore, L2 is a commutator for Lz. For the L2 and Lz operations, what are the associated eigenvalues for the |l, m eigenkets? If the magnetic quantum number ml is an eigenvalue of the orbital angular momentum L = Lx iLy, as is often the case, then

$$\hat{L}z\,|l, ml\rangle = mlk|l, ml\rangle$$

It is required that the azimuthal quantum number, l, satisfy the following for every ml integer:

$$\hat{L}2|l, ml\rangle = k2l(l + 1)|l, ml\rangle$$

Constructing the matching L2 eigenvalues

The eigenkets...what are they? The operators of Hamiltonian H V (x, t) end up creating a sphere in (x, y, z) (r sin θ cos φ, r sin θ sin φ, r cos θ), in the Schrodinger model, which is particularly helpful for demonstrating them.

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$$\begin{cases} L_z &= -i\hbar\left(\sin\phi\frac{\partial}{\partial\phi}\right) \\ L_y &= -i\hbar\left(\cos\phi\frac{\partial}{\partial\theta} - \cot\theta\sin\phi\frac{\partial}{\partial\phi}\right) \\ L_x &= i\hbar\left(\sin\phi\frac{\partial}{\partial\theta} - \cot\theta\cos\phi\frac{\partial}{\partial\phi}\right) \\ &\vdots \end{cases}$$

$$\Rightarrow \begin{cases} L^2 &= -\hbar^2\left(\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial}{\partial\theta} + \frac{1}{\sin^2\theta}\frac{\partial^2}{\partial^2\phi}\right) \\ H &= \frac{\hbar^2}{2\mathrm{m}}\left(-\frac{1}{r^2}\frac{\partial}{\delta r}r^2\frac{\partial}{\partial r} + \frac{L^2}{\hbar^2 r^2}\right) + V(r,\theta,\phi) \\ &\vdots \end{cases}$$

and thereby modifying the Schrodinger equation's original form. The spherical harmonics, a specific collection of functions, are more conveniently written as the Eigen functions ψ(θ, φ) of L2 in this notation.

$$\psi_{lm}(\theta,\phi) = \sqrt{\frac{2l+1}{4\pi}\frac{(l-m)!}{(l+m)!}}P_{lm}(\cos\theta)e^{im\phi}$$

and the corresponding Legendre function is Plm. Among the many fascinating features of these lms is the need that the quantum numbers in Equations l = ml = l and l, ml be integers.

Example: Hydrogen Atom

Solving the wave functions of a hydrogen atom, which only includes one proton (represented by the subscript p) and one electron (represented by the subscript e), is a classic application of the Schrodinger equation. Since solving these difficult equations is beyond the scope of this thesis, we merely provide the crucial details here.

For illustration, let us use as the Eigen function that solves the time-independent Schrodinger equation for a proton with a simple Coulomb potential, V (r) − 4πϵ0r , with ϵ0 where 0 is the permittivity of vacuum.

Strictly speaking, the mass of the system is, the decreased mass, but for the sake of brevity, we'll just call it "the mass," or "m." We suppose that Φ(r, θ, φ) may be broken down into radial functions, (r), and angular functions, Φ(r, θ, φ) in order to solve H = E. The (global) Schrodinger equation may be modified by substituting the following expressions:

$$\Phi(r,\theta,\phi) = \rho(r)\psi(\theta,\phi)$$

$$\rightarrow \frac{\hbar^2}{2m} + \left(\left[-\frac{1}{r^2}\frac{\partial}{\partial r}r^2\frac{\partial\rho(r)}{\partial r}\right]\psi(\theta,\phi) + \left[\frac{\rho(r)}{\hbar^2 r^2}\right]\underbrace{L^2\psi(\theta,\phi)}_{\hbar^2 l(l+1)\psi(\theta,\phi)}\right) - \left(\frac{e^2}{4\pi\epsilon_0 r} - E\right)\Phi = 0$$

$$\rightarrow \left[\frac{\hbar^2}{2m}\left(-\frac{1}{r^2}\frac{\partial}{\partial r}r^2\frac{\partial}{\partial r} + \frac{l(l+1)}{r^2}\right) - \frac{e^2}{4\pi\epsilon_0 r} - E\right]\rho(r) = 0$$

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We get the well-studied mathematical solutions to the Sturm-Liouville problem for (r). In the presence of well-defined boundaries, the energy E can only take on finite quantities: E = −13.6eV, for n > 1 and l = 0 . . . n − 1.

Spin Angular Momentum

The fundamental ideas of quantum mechanics culminate in the introduction of spin, a kind of angular momentum that is unique to quantum mechanics. Hermitian operators S = (Sx, Sy, Sz) are defined in a way that complies with the commutation rules of operator L. The appropriate eigenvalues are defined by Sz and S2 as operators in the new basis |s.ms, as

$$S^2|s, m_s\rangle = m_s\hbar|s, m_s\rangle$$
$$S_z|s, m_s\rangle = s(s+1)\hbar^2|s, m_s\rangle$$

Where ms = {−s, −s + 1, . . . , s − 1, s}. Electrons and protons are examples of fermions because their spin numbers are only half an integer (s = 1), whereas photons are an example of a boson since their spin number is$_2$an integer (s = 1).

CONCLUSION

Although our values are within 2 of those found in the literature, we are unable to draw firm conclusions about the flux or brightness of the unidentified nebulae due to the ambiguity in flux calibration. The uncertainty seems to be inherent to the procedure, rather than being attributable to our specific collection of observations, the fact that we subtracted V pass band pictures instead of B + V, or the absence of absolute calibration in photometry due to the lack of photometric nights. Although the discrepancy between our measurements and amounts to just 0.4 ADU per pixel, it is virtually impossible to ensure that background determination employed in picture subtraction is done to within a fraction of an ADU throughout the whole field of view. Despite our best efforts, we were unable to make sense of the data presented by HOTPANTS when subtracting photographs captured with various filters, including the subtraction between V-V and O-O filters of successive images.

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