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Analyzing the Elements of X-ray Emission Spectrum of C/1999 S4 (LINEAR) and 9p/ Tempel 1 Comets

Ruaa Faraj Hanash*, Salman Zaidan Khalaf, Khaleel I. Abood
Department of Astronomy and Space, College of Science, University of Baghdad, Baghdad, Iraq

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Abstract
The study focused on the elemental abundance of two different comets. These comets were observed at an energy range of (100-10000) eV. The X-ray emission spectrum was analyzed and the results showed that comet C/1999 S4 (LINEAR) from the Oort cloud region (long-period) and comet 9p/Tempel 1 from the Kuiper Belt region (short-period) had the highest abundances of the different elements. The ds9 program used data from NASA's Chandra analysis to show the spectra of these comets and analyze their elements. The results showed that some elements were similar in all comets, such as (Carbon (C), Oxygen (O), Neon (Ne), and Silicon (Si)). While others varied from one comet to another, such as (Magnesium (Mg) and Chlorine (Cl)) elements which appeared in the C/1999 S4 (LINEAR) comet, and (Aluminum (A) and Phosphors (P)) elements which appeared in the 9P/Tempel 1 comet. This is due to these comets' areas of presence, where the elements of comets can be classified through their areas of presence.

Keywords: X-ray, Comets, Spectroscopy, Solar wind, Chandra Telescope.

تحليل عناصر طيف انبعاث الاشعة السينية للمذنبات C/1999 S4 (LINEAR), 9p/ Tempel 1

رؤى فرج حنش, سلمان زيدان خلف,خليل أبراهيم عبود
قسم الفلك والفضاء، كلية العلوم، جامعة بغداد، بغداد، العراق

الخلاصة
ركزت الدراسة على الوفرة الأولية لمذنبين مختلفين, ولوحظت هذه المذنبات في مدى طاقة (100-10000) ألكترون فولت. تم تحليل طيف أنبعاث الأشعة السينية, وأظهرت النتائج أن المذنب C/1999 S4 (LINEAR) من منطقة سحابة ورت (زمن دورة طويل) والمذنب 9P/Tempel 1 من منطقة حزام كويبر (زمن دورة قصير), يمتلكان أعلى وفرة من العناصر المختلفة, حيث تم أستخدام برنامج ds9 لتحليل بيانات شاندرا التابع لناسا لعرض أطياف هذه العناصر وتحليل عناصرها. أظهرت النتائج ان بعض العناصر متشابهة في جميع المذنبات مثل (الأوكسجين (O) والسيليكون (Si) والنيون (Ne)), بينما هنالك عناصر تتغير من مذنب ألى اخر مثل المغنتيسيوم ((Mg) والكلورين (Cl)) وهي عناصر ظهرت في المذنب C/1999 S4 (LINEAR), بينما العناصر (الألمنيوم (Al) والفسفور (P)) ظهرت في المذنب 9P/Tempel 1, هذا التغير بسبب مناطق تواجد المذنبات حيث يمكن تصنيفها من خلال مناطق تواجدها.

*Email: ruaafarag923@gmail.com

1. Introduction

X-rays are a type of electromagnetic spectrum that is made up of photons with high energies (120 eV to 120000 eV) and short wavelengths (0.1 to 100 nm) [1, 2]. The released X-ray emission from the comet is caused by solar particles that collide with the comet's atmosphere. Although hydrogen and helium atoms make up the majority of the solar wind's particles [3], relativity-heavy atoms are responsible for the observed X-ray emission (oxygen or carbon).

These atoms have their electrons taken away, resulting in excited ions [4], and meeting neutral atoms in the comet's atmosphere through collisions. A process known as "charge exchange" occurs when an electron is transferred between one of these neutral atoms, often hydrogen, and a heavy atom in the solar wind. After such a collision, the caught electron goes into a tighter orbit and emits an X-ray [5]. Solar Wind Charge Exchange (SWCX) occurs on comets, which causes them to generate X-rays. One or more electrons are donated to the excited energy level of a highly charged solar wind ion by gas in the comet's coma. An X-ray photon is released when the ion relaxes after that [6].

In 2014, S. Z. Khalaf calculated the ion tail temperature of comet ISON using MHD hydrodynamic magnetic laws. MHD equations were solved numerically using Matlab simulation code by the Cubic volume element method [7].

In 2020, Salman Z. Khalaf and Khaleel Ibrahim obtained the X-ray spectrum for 23 elements of comet PanSTARRS C/2011 S4, where they found that the carbon element has a high abundance and the gold element is second in order of abundance, from which the velocities of the elements were calculated and the gas temperature of the comet was calculated [8].

In 2022, Rasha S. Najm et al. presented X-ray spectra resulting from the solar wind charge exchange for Near-Asteroid Belt Comets. They were focused on the abundance of elements in six different comets, including 17P/Holmes, C/1999T1, C/2013A1, 9P/Tempel1, and 103p/Hartley 2(NEAT) [9].

On 30 Jan 2023, Rasha S. Najm et al. presented the distributions of 100 comets concerning heliocentric distances. They showed that 54% of comets were nearby the asteroid belt, but only 11% in the Kuiper belt and 35% in the Oort cloud [10].

2. Physical Model:

2.1 Determination of the Apparent Magnitude Distributions

In astronomy, the term apparent magnitude is used to describe the measurement of an object’s brightness as seen from the Earth.

Modern telescopes have integrated charge-couple devices (CCDs), which observe the incoming light from a celestial object. The apparent magnitude of the comet can be calculated by measuring the comet light recorded on the CCD and using it in the formula for apparent magnitude.

We calculate the apparent magnitude of the comets using eq. (1) [11]:

$$\boldsymbol{apperant\ magnitude\ (m) = -2.5 \log\ (intensity)} \quad (1)$$

Here, 'intensity', also known as 'counts', refers to the amount of light that is emitted from the object and received by the CCD.

2.2. Determination of the Wavelength Distributions

The photon energy is defined as an eq. (2) [1]:

$$E = hf \quad (2)$$

Where: E = energy, h = plank's constant, and f = frequency

The speed of light $c = f\lambda$ energy as equation (3)

$$E = hc/\lambda \quad (3)$$

Where c = speed of light and λ= wavelength

3. Result and Discussion:

3.1 C/1999 S4 Comet

The comet C/linear 1999 S4 was found on September 27, 1999 [12]. It is a long-period (high parabola) comet. This comet's eccentricity (e=1.00010) indicates that it was likely formed in the Oort cloud over 200 years, as shown in Figure 1.

Figure 1: Represents the C/ Linear 1999 comet [13].

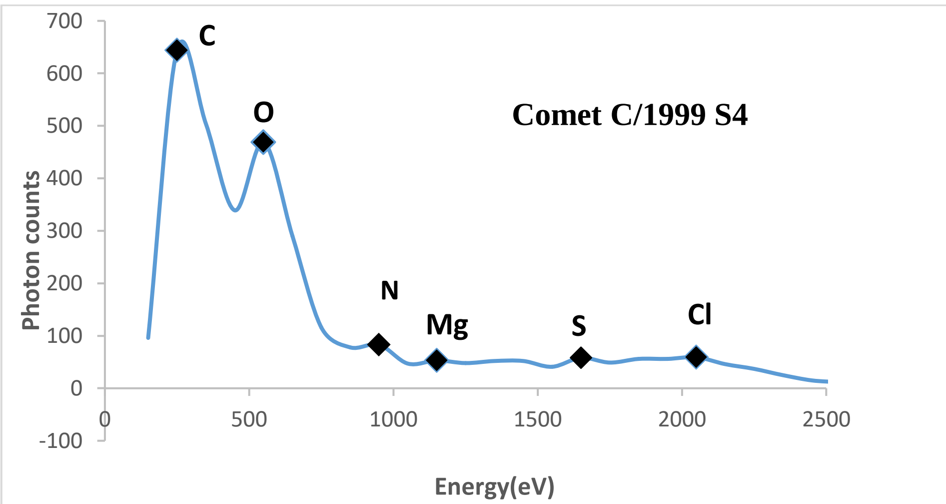

Figure 2: Relation between photon counts vs. energy (eV) for comet C/1999 S4.

Figure 2 shows the spectrum of the C/1999 S4 comet. Note that there are six clear peaks, and each vertex represents a specific substance, depending on the standard energy of materials, as shown in Table (1), where each material in the universe has a specific energy similar to a fingerprint. The materials that have high photon counts and low energies are Carbon (C) at (energy 250 eV, photon counts 644), Oxygen (O) at (energy 550 eV, photon counts 469), and Neon (Ne) at (energy 950 eV, photon counts 83). While the materials that have low photon counts and high energies are Magnesium (Mg) at (energy 1250 eV, photon counts 53), Silicon (Si) at (energy 1650 eV, photon counts 58), and Chlorine (Cl) at (energy 2050 eV, photon counts 59) as shown in Figure 2. The observed and standard energies for materials are shown in Table (1).

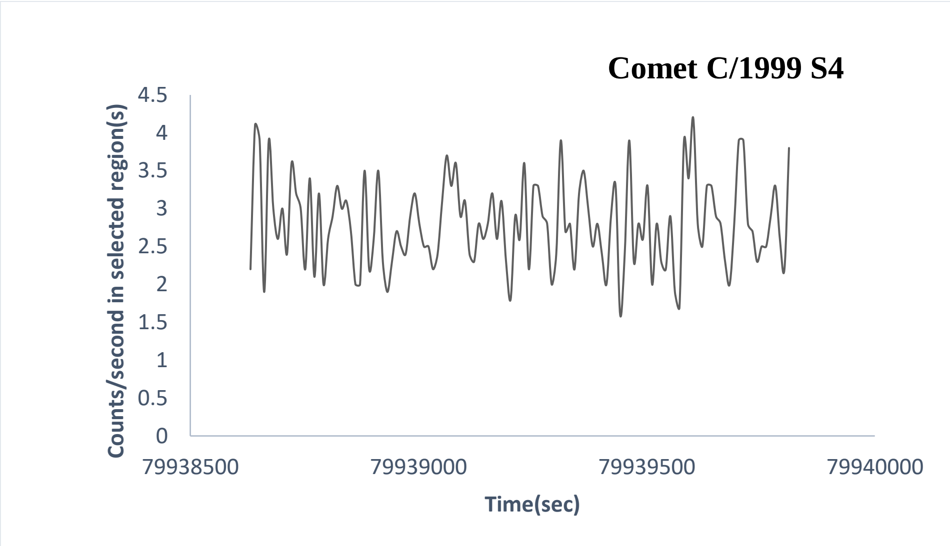

Figure 3: The relation between counts/second in the selected region(s) vs. time(sec) for comet C/1999 S4.

The light curve is depicted in Figure 3, a graph of a comet's light intensity as a function of time, with the amount of light on the y-axis and time on the x-axis. Light curves can be periodic or non-periodic, but the curves on this comet (C/1999 S4) are non-periodic.

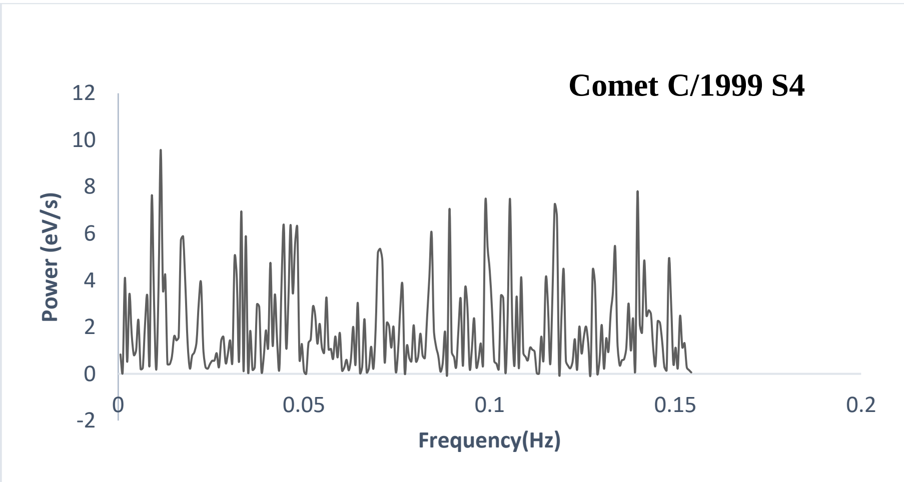

Figure 4: The relation between power (eV/s) vs. frequency(Hz) for comet C/1999 S4.

Figure 4 shows the relationship between power and frequency, as shown in equation (2). The power is directly proportional to the frequency. The frequency is inversely proportional to the time. So you can see the maximum value (power and frequency) for comet C/1999 S4 (0.011444984 – 9.85).

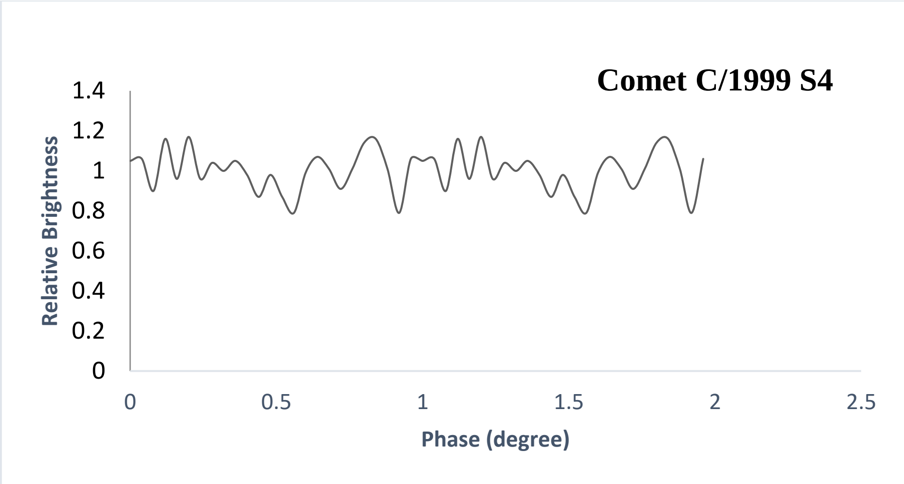

Figure 5: Relative brightness vs. phase relation for comet C/1999 S4.

Figure 5 shows the relationship between the comet's brightness and phase angle. Given that the comet's phase angle at the time of observations ranged from 0 to 2 degrees, the brightness of the comet was highest at 1.2 degrees and lowest at 0.8 degrees.

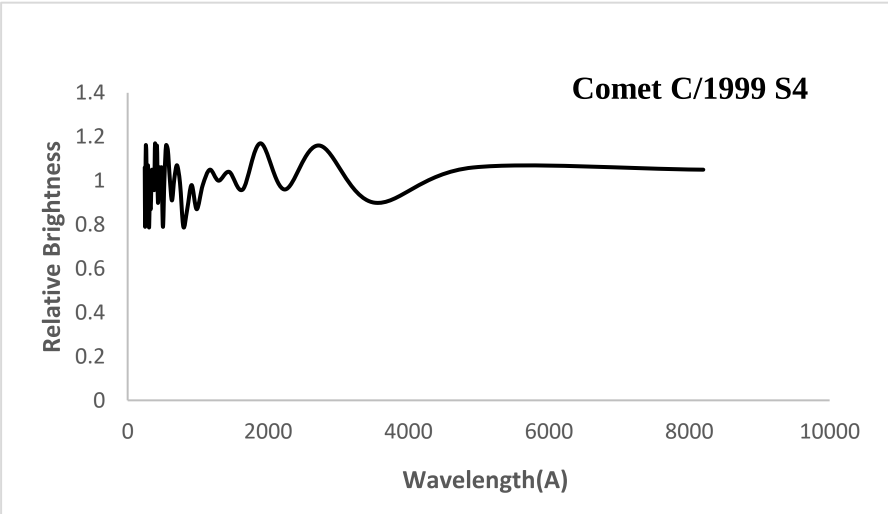

Figure 6: The relation between relative brightness vs wavelength A^o for comet C/1999 S4.

The physical properties of X-rays are a shorter wavelength, a higher frequency, and a higher energy. The limits of X-ray wavelengths are not sharply defined, there is always an overlap with the ultraviolet region towards the longer wavelength side and with the gamma-ray region towards the shorter wavelength side. According to this figure, we can classify the X-ray spectrum depending on wavelength as ultrasoft X-rays because the wavelength is greater than (10) A^o.

3.2 9p/Tempel 1 Comet

The comet 9p/Tempel1 orbits the sun once every 5.5 years and belongs to the periodic Jupiter family. It was discovered by Wilhelm Tempel in 1867 [14].

Figure 7: Represents the 9p/Tempel 1 comet [15].

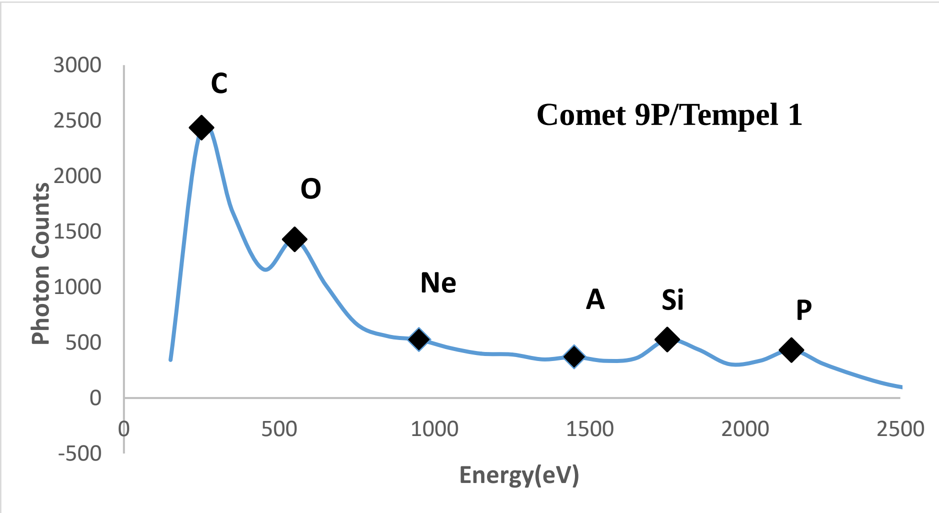

Figure 8: The relation between photon counts vs. energy (eV) for comet 9P/Tempel 1.

Figure 8 shows the spectrum of the 9P/Tempel 1 comet. Note that there are six clear peaks, and each vertex represents a specific substance, depending on the standard energy of materials as shown in Table (1), where each material in the universe has specific energy similar to a fingerprint. The materials that have high photon counts and low energies are Carbon (C) at (energy 250 eV, photon counts 2436), Oxygen (O) at (energy 550 eV, photon counts 1429), and Neon (Ne) at (energy 950 eV, photon counts 525). While the materials that have low photon counts and high energies are Aluminum (A) at (energy 1450 eV, photon counts 370), Silicon (Si) at (energy1750 eV, photon counts 526), and Phosphorus (P) at (energy 2150 eV, photon counts 432), as shown in Figure (2-2). The observed and standard energies for materials are shown in Table (2).

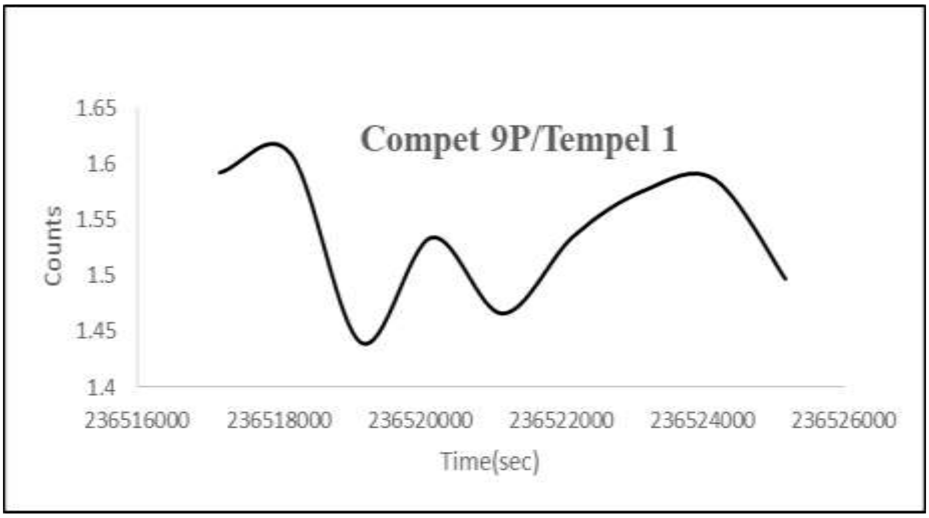

Figure 9: The relation between counts in the selected region(s) vs time (sec) for comet 9P/Tempel 1.

Light curves represent the brightness of comet 9P/Tempel1 over time. In the study of comets that change their brightness over time, as shown above in Figure 9, we note that the height brightness is the highest value (1.62).

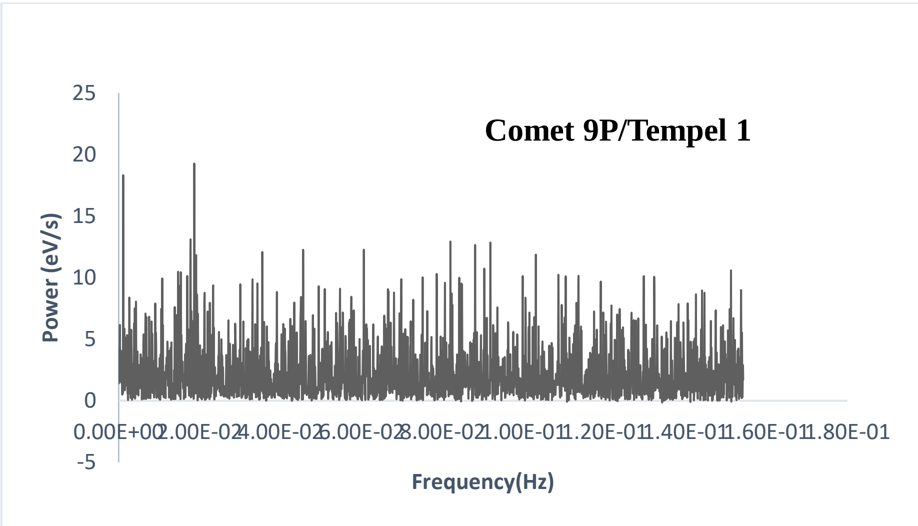

Figure 10: The relation between powers (eV/s) vs. frequency (Hz) for comet 9P/Tempel 1.

Figure 10 depicts the power-frequency relationship, shown in equation (2). The relationship between frequency and power is linear. Time and frequency are negatively related. As a result, you can see the comet 9P/Tempel 1's maximum value (intensity and frequency) of (0.01868131 - 19.27).

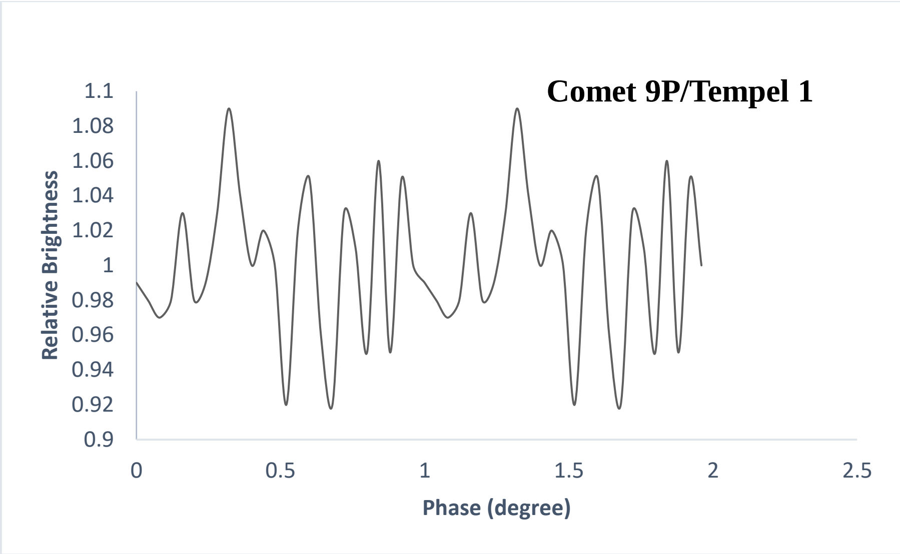

Figure 11: The relation between relative brightness vs. phase (degree) for comet 9P/Tempel 1.

Figure 11 shows the relationship between the brightness of the comet as a function of the phase angle, knowing that the phase angle of this comet passed between 0^o-2^o, if the phase angle is close to zero, the brightness is high value (1.1^o), but if the phase angle is relative to 2, the brightness of this comet is low value (0.91^o).

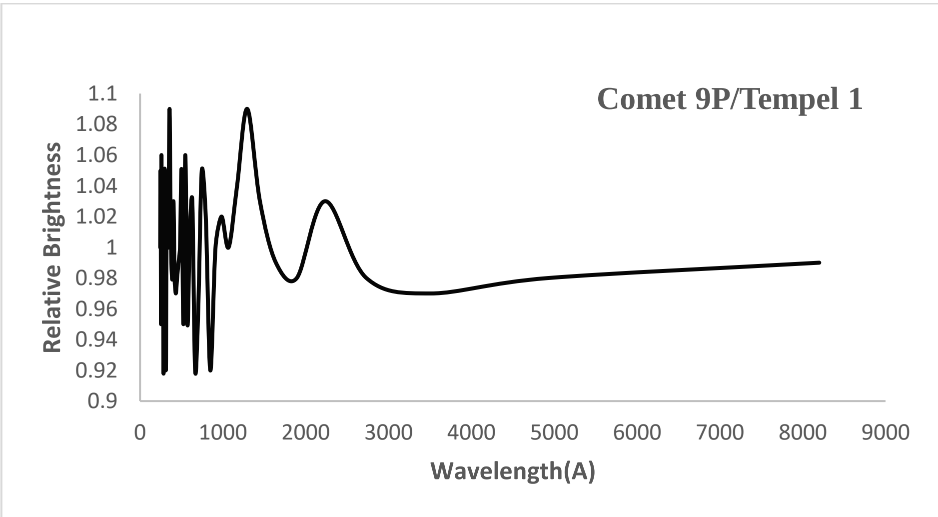

Figure 12: The relation between relative brightness vs. wavelength (A) for comet 9P/Tempel 1.

The brightness of the light is related to intensity, or the amount of light of comet emits or reflects. The brightness depends on the amplitude and the height of the wavelength. The maximum brightness is 1.08, and the wavelength is 1294 A^o.

Table 1: The results of the materials found in comet C/1999 S4 with the observed and standard energies

Material	Observed energy (eV)	Standard energy (eV)
C-Carbon	250	277
O-Oxygen	550	524.9
Ne-Neon	950	848.6
Mg-Magnesium	1250	1253.60
Si-Silicon	1650	1739.98
Cl-Chlorine	2050	2622.39

Table 2: The results of the materials found in comet 9P/Tempel 1 with the observed and standard energies

Material	Observed energy (eV)	Standard energy (eV)
C-Carbon	250	277
O-Oxygen	550	524.9
Ne-Neon	950	848.6
Al- Aluminum	1450	1486.70
Si-Silicon	1950	1739.98
P-Phosphorus	2150	2013.7

4. Conclusions

From the results, the following conclusions are reached:

1- The structure and behavior of comets can be described by Chandra data analysis.

2- From the results, the common elements for both comets are (C, O, Ne, and Si), as shown in Figures 2, 8.

3- The observed spectra from both comets provide us with information about the composition of the region where the comet comes from.

4- The two comets, analyzed in this research, contain carbon because it is the fourth most abundant element in the universe.

5- It found characteristic elements (Mg and Cl) in the C/1999S4 comet and (Al and P) in the 9P/Tempel 1 comet. These materials are heavy and have little abundance in both comets depending on the value of photon counts, as shown in Figures 1, 8.

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