X-ray astrophysics and cosmology	Vật lý thiên văn và vũ trụ học tia X
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First, astrophysical applications of X-ray technics are briefly presented. Then, essential X-ray investigations directly relevant to cosmology, viz. detection of hot intracluster and intergalactic gas are described. The role of the X-ray observations in investigation of supermassive black holes is characterized.	Trước hết, chúng tôi trình bày ngắn gọn những ứng dụng của kỹ thuật tia X trong vật lý thiên văn. Sau đó, mô tả những khám phá tia X cơ bản có liên quan trực tiếp đến vũ trụ học, chẳng hạn như (tức là) phát hiện ra các khí nóng gần trung tâm của cụm thiên hà và giữa các thiên hà. Đồng thời chúng tôi cũng làm rõ vai trò của các quan sát tia X trong việc nghiên cứu các lỗ đen có khối lượng khổng lồ.
1. Introduction: The article is based on my two lectures presented during the School Introduction to cosmology held in Kielce 15–25 July 2015. The first significant accomplishments in X-ray astronomy date back to the 1960s. Thus, they were contemporary to the discovery of the cosmic microwave background (CMB) radiation. It may be that the cosmological implications of the X-ray exploration of the Universe are not as fundamental as the CMB measurements. Nevertheless, high energy astrophysics has changed our perspective, and in some instances, our understanding, of various processes and phenomena essential to cosmology. The present article should not be regarded as a systematic review of the literature on cosmology. Here I focus the attention on a few points where the X-ray observations appeared to be crucial for the very perception of the astrophysical objects. The selection of questions is subjective and skewed towards those related to my own research. Also, most of the information is limited to soft X-rays, i.e. below ∼ 10 keV. Observational	1.Giới thiệu: Bài báo này dựa theo hai bài giảng của tôi trong Lớp học Nhập môn vũ trụ học được tổ chức tại Kielce từ ngày 15 đến 25 tháng 7 năm 2015. Các bài giảng này trình bày những thành tựu quan trọng nhất của ngành thiên văn học tia X từ những năm 1960 cho đến nay. Đây cũng là khoảng thời gian các nhà khoa học tiến hành nghiên cứu bức xạ phông nền vũ trụ (CMB). Có thể, ý nghĩa về mặt vũ trụ học của các nghiên cứu tia X không quan trọng (cơ bản) bằng các phép đo CMB. Tuy nhiên, vật lý thiên văn năng lượng cao đã thay đổi quan điểm của chúng ta, và trong một số trường hợp là hiểu biết của chúng ta về các quá trình và các hiện tượng khác nhau đóng vai trò quan trọng trong vũ trụ học. Bài báo này sẽ không tổng quan toàn diện các nghiên cứu về vũ trụ học. Ở đây, tôi tập trung vào một vài điểm trong đó các quan sát tia X đóng vai trò quan trọng để hiểu (nhận thức) về các thiên thể. Việc lựa chọn các câu hỏi theo quan điểm chủ quan và nghiêng về những câu hỏi có liên quan đến nghiên cứu của cá nhân tôi. Tương tự, đa phần

cosmology by its nature is related to extragalactic astrophysics. And in fact, the X-ray observations of some classes of extragalactic objects have yielded information of cosmological importance. First, new ‘phase’ of matter, viz. the hot gas in clusters of galaxies, was discovered by means of the X-ray devices flown above the Earth’s atmosphere. It also now appears that the hot gas surrounding field galaxies has been detected in X-rays. Thus, X-ray observations have contributed to the solution of the ‘missing baryon’ problem. Most of the X-ray background (XRB) has been resolved into a large number of discrete extragalactic sources. Since the great majority of these sources are associated with active galactic nuclei (AGN), it was realized that supermassive black holes are common in the Universe and reside in the centres of almost all large galaxies. This conclusion raised a question that is still not fully understood: what processes were responsible for apparently rapid growth of central mass concentration in the early stages of galaxy evolution? Below I discuss these topics in detail, but first I would like to recall the basic X-ray technicalities in an astrophysical context that make high energy observations and telescopes distinctly different from optical ones. In most cases I only mention the problem or give an illustrative example. Obviously, the reader is advised to searchthe literature on all the questions indicated in the next section, as well as in the subsequent material on the relevance of X-rays to astrophysics.	những thông tin trình bày ở đây giới hạn ở tia X mềm, tức là dưới 10 keV. Bản chất của vũ trụ học quan sát có liên quan đến vật lý thiên văn ngoài thiên hà. Và thực sự, những quan sát về tia X của một số loại vật thể ngoài thiên hà đã mang lại những thông tin vũ trụ học quan trọng. [redacted]

2. X-ray telescopes and detectors: The Earth’s atmosphere is opaque to all radiation of wavelengths shorter than ∼ 330 nm. Because of that, X-ray astronomy detectors have to be flown above the atmosphere, and the history of X-ray astronomy spans just a little more than 50 years. A pioneer period based on detectors equipped with slat collimators provided fascinating information on individual sources. However, the X-ray technique reached maturity with the advent of the imaging reflecting telescopes.In the X-ray domain, the refractive index is smaller than 1 but the difference is extremely minute. As an example, the refractive index of gold for 10 keV photons amounts to 0.99997 = 1 − 3 −5 . To avoid absorption in the mirror material, the condition of total internal reflection has to be satisfied. Therefore, the incidence angle has to be large, or the grazing angle, small. This feature determines the specific shape of the X-ray mirror. It has a barrel like shape rather than the well recognizable concave disk (Figs. 1 and 2). A single parabolic mirror yields undistorted images only within a small area around the optical axis. Off-axis distortions are particularly severe in X-ray constructions. To improve the image quality over an adequate field of view, a combination of two mirrors is commonly used.The effective area of small grazing angle mirrors is also small. With typical grazing angles of . 1 ◦ the entrance aperture is reduced by a factor of ∼ 60. To increase the collecting area,

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mirrors are nested within one another. In the Chandra telescope, 4 confocal paraboloid-hyperboloid pairs constitute the High Resolution Mirror Assembly, while the XMM-Newton and NuSTAR telescopes have 58 and 133 Wolter I mirrors, respectively. The total geometric area, Ageom of the mirror collection reaches1100 cm2 for Chandra and 6000 cm2 for XMM-Newton. Two basic parameters define the X-ray telescope capabilities: effective area and angular resolution. Both are usually strongly dependent on the off-axis angle and the photon energy. In virtually all systems, the small linear size of detector pixels in conjunction with large mirror focal lengths do not limit the angular resolution; it is determined by the precision of the mirror figure and the quality of its surface, and it never approaches the diffraction limit. The effective area, Aeff, ultimately determines the number of detected counts, n, from a source with flux f:... where Aeff is in cm2 , f in photons/cm2/s and texp is the exposure time in seconds. The effective area:... where: R(E) is the reflectivity, i.e. the fraction of photons imaged in the focal plane within the area enclosed in the point spread function (PSF), depends on energy, V – vignetting correction, depends on energy and the off-axis angle, and Q(E, pos) – quantum efficiency of the detector, depends on energy and position in the detector plane. A major quantitative difference from the analogous relationships in the optical domain are the strong variations in the X-ray band of all the involved parameters	[redacted]

(e.g. R, V and Q). Moreover, the PSF lacks azimuthal symmetry, usually has a complex shape and degrades markedly even for small off-axis angles. Another serious obstacle impeding observations is background, occasionally highly variable. Generally, the particle background dominates at high energies (mostly because Aeff diminishes), while effects of local X-ray photons prevail in the soft energy bands. The flux of the weakest point-like source that can be detected depends on the Aeff and the angular resolution (and on texp). Thus, the Chandra telescope with its superb resolution of ∼ 0 00 .5 as compared to ∼ 2000 of the XMM-Newton, is better suited to the investigations of weak point sources, while the XMM-Newton, with 5−6 larger Aeff, is more effective for faint, extended low surface brightness objects.

3. Baryon content: Assessments of the total baryon density in the Universe come from at least three independent sources: a) the big bang nucleosynthesis (BBN), b) cosmic microwave background (CMB) fluctuations, and c) Ly-α forest. The BBN line of reasoning is following. Deuterium production in the primeval nucleosynthesis depends strongly on the baryon density and all the subsequent processes tend to reduce its abundance (Burles et al., 2001b). Using measurements of deuterium in high redshift clouds of presumably primordial gas (Tytler et al., 2000), Burles et al. (2001a) get precise determination of the baryon density, where h is the

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‘normalized’ Hubble constant: $h = H_\circ/100$ km $s^{-1}Mpc^{-1}$. Taking the present-day determination of $H_\circ = 70$ km $s^{-1}Mpc^{-1}$, the baryon density amounts to $\Omega b \approx 0.04$. The most recent Wilkinson Microwave Anisotropy Probe (WMAP)determination of the CMB fluctuation power spectrum provide several high precision data on several cosmological parameters (Hinshaw et al., 2013), among others: $\Omega b\ h^2 = 0.02264 \pm 0.00050$, and quoted above the figure of $H_\circ$. Thus, BBN and CMB yield fully consistent estimates of Ωb. The assessment based on observations of the Ly-α are least accurate but concentrate around $\Omega b \sim 0.04$ (Rauch &Haehnelt, 1995). Hence, ‘the first three minutes’, Universe at redshift ∼ 1200, and ∼ 2 all give congruent results.The density of the luminous baryons in the local Universe was a subject of many investigations and there is a general consensus that the luminous matter constitutes a small fraction (perhaps as small as 10 %) of the total baryonic matter (e.g. Persic & Salucci 1992). The early discovery of hot gas in the Coma cluster (Gursky et al., 1971; Meekins et al., 1971), as well as the routine detections of hot gas (residing commonly in rich clusters) by means of the Uhuru satellite (Gursky et al., 1972) has not removed this discrepancy. It revealed, however, the existence of this new constituent of baryonic matter that typically exceeds the mass of all stars in the cluster at least by a factor of 3. Moreover, the X-ray emission of the intracluster gas yielded a new method to study the distribution of dark matter in

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clusters. Under the natural and reasonable assumption that both cluster constituents viz. baryonic and dark (non-baryonic) matter remain in hydrostatic equilibrium, the surface brightness distribution of X-ray emission by the hot gas allows one to determine the space distribution of the gravitational potential.1 Using the images obtained with the Einstein Observatory, the first satellite with the imaging telescope on board, Fabricant et al. (1980) assessed that the galaxy M87 is surrounded by a dark halo extending to ∼ 230 kpc with a mass between 1.7 × 1013M. The question of the ‘missing baryons’ has not been fully resolved. Nevertheless, X-ray observations offer the possibility of reducing the divergence between the baryon budget derived from the BBN or CMB and the local estimates based on direct observations. Cen & Ostriker (1999) postulated that a large fraction of unaccounted baryons ‘at the present time having a temperature in the range of 105 − 107 K’ slowly flow towards potential wells created by agglomerations of dark and baryonic matter. Ionized gas shines via free-free emission, or thermal Bremsstrahlung. At temperatures of 106 K typical photon energies reach and exceed 0.1 keV. Accordingly, this warmhot intergalactic medium (WHIM) is expected to emit soft X-rays. Unfortunately, the predicted density of WHIM is very low. Consequently, the thermal emission, which is proportional to density squared, is also extremely weak. Assuming that a halo of WHIM is associated with all normal (i.e. non-dwarf) galaxies, the X-

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ray luminosity of a single halo would be much below the detection limit of the present-day telescopes.Stacking of observations is a standard procedure to get some insight into the average properties of the population of sources with the low S/N ratio. From the XMM-Newton archive I selected a large number of pointings suitable for search of the low surface brightness extended emission (Sołtan, 2006). Above 150 pointings satisfied the relevant criteria, i.e. the pointings were selected at high galactic latitude, without bright point sources. Fields with clusters of galaxies were also excluded. In each pointing a correlation function (CF) of the X-ray surface brightness with field galaxies was determined. The resultant CF signal represented stacking the XRB distributions around 3000 galaxies. The statistical content of the data used to detect the WHIM emission corresponded to a single exposure of ∼ 5 × 107 s, an order of magnitude exceeding the ultra deep Chandra exposure. Since the WHIM emission is expected to be substantially softer than the cluster emission, the crucial test for the detection of the WHIM was a positive amplitude of the CF between the field galaxies and the soft XRB and no correlation with the harder flux, say at energies above ∼ 1 keV. The results have confirmed these predictions. The correlation signal was clearly visible below 1 keV, while no extended emission above 1.5−2 keV was detected. The emission confined to genuine low energies assures us that no hypothetical flux from unknown clusters is mistakenly identified with the WHIM

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emission. Although the correlation signal is statistically significant, our estimates of the mass of the emitting gas are subject to large uncertainties. We assess that the WHIM accumulated in halos around galaxies that generated the XRB enhancements discovered via the correlation analysis, contributed 8–19 % of the Ωb (So ltan, 2006). It means that still substantial fraction of baryons in the local Universe remains dark. Stacking of observations revealed some average properties of the WHIM halos. The detailed X-ray study of the individual mass concentrations around galaxies will require more powerful instruments. We assess that the Athena observatory will be capable to provide essential data on the WHIM distribution. Athena is an ESA mission planned for launch in 2028. Although many instrument specifications are still under consideration, it has been decided that the diameter of the X-ray mirror will reach at least 2380 mm, allowing for the entrance aperture of 1.5–2 m2.	[redacted]
4. Supermassive black holes in the Universe:Astrophysics of active galactic nuclei (AGN) began in the 1960s with the first measurements of quasar redshifts (Schmidt & Matthews, 1964). Conspicuously small linear sizes plus large quasar distances, implying huge absolute luminosities, demonstrated that nuclear energy reservoirs in any kind of astrophysical objects may be too shallow to keep quasars alive for sufficiently long periods of time. It became clear that only matter accreting onto supermassive black hole (SMBH) acquires adequate amounts	[redacted]

of gravitational energy that can be converted into the observed radiation. A ratio of the total (bolometric) AGN luminosity to the mass accretion rate is determined by the efficiency of the energy conversion, κ. Thus, all the AGN emission is inevitably associated with the mass accumulation in the SMBH. Early quasar observations indicated that the number density of luminous quasars in the past was substantially larger than that observed locally. Still, it seemed that quasar-like activity in the galaxy nuclei is fairly occasional, and most of galaxies have never experienced the AGN phase. Deep X-ray exposures with the Einstein Observatory (Giacconi et al., 1979), ROSAT (Hasinger et al., 1993), Chandra and some others satellites revealed that: a) quasars as a rule emit large amount of energy in the X-ray domain, and b) most of the XRB is generated by the AGN. Alongside to the observational advances, the joint effort of many astrophysicists led to the construction of the AGN model unifying quasars, Seyfert galaxies and radiogalaxies. Quasars appeared to be just the most luminous AGN. In this way, AGN became quite typical objects in the Universe, which seemed to contradict the apparent notion that SMBH are rare objects. The ease with which AGN are detected in X-rays has allowed us to assess the average number of AGN per unit volume.The line of reasoning follows(Soltan, 1982).Local radiation density produced by all the AGN in the Universe:... where S denotes the bolometric AGN flux, and dN/dS are the AGN number counts. One can assess the

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AGN bolometric flux using the X-ray band. This is based on the average spectral energy distribution of a large number of AGN. Now we assume that the Universe is homogeneous at large scales and the Milky Way is situated in a ‘typical’ position in the Universe. Thus, the observed local energy density produced by all the AGN has to be equal to the energy produced locally in the unit volume over all the cosmological epochs. Because the Universe is expanding, the radiative energy is redshifted, and the above simple relationship is modified. Accordingly, the energy emitted in a unit volume by all the AGN. where now the AGN number counts, N(S, z), depend also on redshift z. The total mass accumulated in all the SMBH in a unit volume, m = E/(c 2 κ), and the average SMBH mass per galaxy MSMBH = m/n, where n is the space density of galaxies. Although models do not constrain the conversion factor, it is generally accepted that κ < 0.3. The upper limit on κ determines the lower limit on m and MSMBH. Straightforward estimates of all the involved quantities show that virtually each galaxy in our neighbourhood contains a SMBH. Later observations confirmed the above conclusion: most galaxies, at least those with central condensation, seem to host a SMBH with masses spanning a wide range of ∼ 106 − 1010 M and 4 × 1013M	[redacted]