Using active galaxies as standard candles: Is dust the culprit behind discrepancies?

Background

How and when did the Universe start? When did the first stars and galaxies form? What is the fate of the Universe?

The standard cosmological model also known as ΛCDM can answer most of these questions, including the properties of the large-scale structure of the Universe - both in its current form as well as in the past past when the first structures were just emerging. In this benchmark model, which is largely consistent with observations, the cosmological constant Λ representing dark energy constitutes approximately 70% of the total energy budget in the current Universe and is responsible for the accelerated expansion of the Universe, first revealed using supernovae type Ia. The remaining 30% of the energy budget is formed by matter that is dominated by still unknown dark matter, while normal baryonic matter found in stars, planets, and humans constitutes only about five percent.

Despite many successes, the last ten years of local supernova measurements and the analysis of cosmic-microwave background led to several discrepancies among cosmological parameters, which could hint at problems with the standard model of cosmology under the assumption that the data are not systematically flawed. In particular, there has been a significant difference in the measured expansion rate or the Hubble constant when the value determined from the cosmic-microwave background measurements is compared with the local observations of supernova explosions. To see whether the difference is due to systematic problems with individual datasets or there is a real problem with the ΛCDM model, alternative cosmological probes are searched for. One of them are quasars, which are active galactic nuclei hosting accreting supermassive black holes, that can be detected from the local Universe to the epoch when the first galaxies were just forming, thus bridging local measurements of supernovae with distant cosmological probes, such as cosmic microwave background. Can quasars help us to solve the current cosmological tensions?

Two methods

It may seem strange how active galactic nuclei (AGN), which are rather complicated objects with supemassive black holes masses spanning five orders of magnitude as well as largely different accretion rates, could be standardized in an analogous way to pulsating or exploding stars. During the last thirty years, as more multi-wavelength data were accumulated, two important correlations were found in AGN, both of which involve an ultraviolet ionizing flux coming from the inner accretion flow around the central black hole.

The first relation is based on the correlation between the UV and the X-ray luminosities (UV/X-ray relation). Both of these luminosities are connected in most active galactic nuclei and their mutual relation is non-linear, which allows to derive the luminosity distance to each source. The luminosity distance as a function of the source redshift essentially yields the Hubble diagram of quasars, which can be used to test different cosmological models, including ΛCDM.

Second, the ionizing luminosity was found to be correlated with the radius of the region, where fast clouds are orbiting around the central black hole. The motion of these clouds is revealed via very broad emission lines whose flux is variable. Moreover, the flux variability is typically correlated well with the variability of the ionizing flux coming from the inner accretion flow. This can be explained using the simple geometrical model, in which the radiation of the inner accretion flow is intercepted by the fast-orbiting clouds. By comparing the variable emission of the clouds with the flux of the accretion disc, it is possible to measure the time delay between the central black hole and the broad-line region, and hence to infer the broad-line region radius. This observational technique is known as

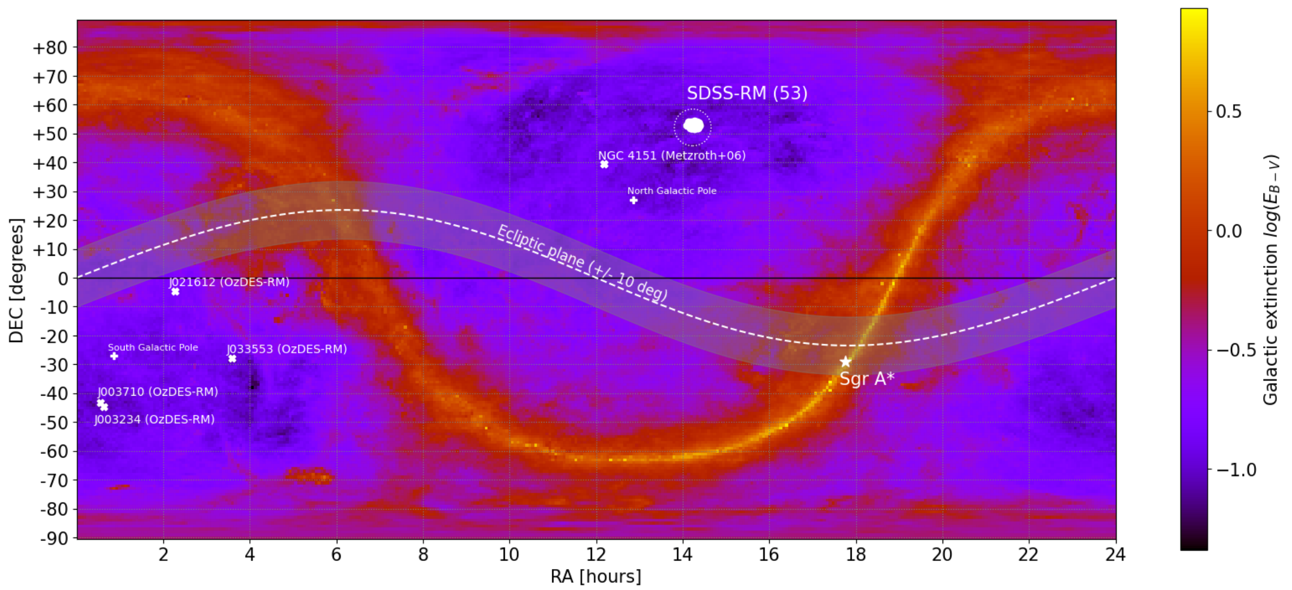

Figure 1: Location of the studied sample of 58 quasars, for which both UV/X-ray and radius-luminosity correlations could be studied with the goal of comparing the determined cosmological parameters.

the reverberation mapping and over the last 30 years the radius-luminosity relation was established for several hundred sources. Given the radius-luminosity relation, the knowledge of the radius allows one to determine the absolute luminosity of the source. From the measured flux, one can determine the luminosity distance for each source, and therefore construct again the Hubble diagram of the quasar population, which can directly be used for cosmological applications.

The question remains if it is possible to find a sample of active galactic nuclei, for which both relations can be studied. Consequently, the determined luminosity distances and cosmological parameters can be checked for consistency.

Discrepancy in luminosity distances

Such a sample of 58 quasars was found and studied by Narayan Khadka (Stony Brook University, formerly at the Kansas State University) and his colleagues, who determined that the two relations (UV/X-ray and radius-luminosity) lead to quite different luminosity distances to the same source (Khadka et al., 2023), which should not happen unless other effects are involved. Moreover, the cosmological parameters obtained from these relations are divergent, with the UV/X-ray relation preferring a larger matter content of the present-day Universe in comparison with the radius-luminosity relation. Moreover, the cosmological parameters determined from the UV/X-ray relation are in discrepancy with the constraints from standard cosmological probes. Therefore, it was a puzzle what could cause such a discrepancy.

Role of dust in galaxies

When one constructs histograms of the differences between the two luminosity distances for the whole quasar sample of 58 sources, it is apparent that the peak of the distribution is shifted to the positive values. In other words, the luminosity distance determined from the UV/X-ray relation is systematically larger than the distance inferred from the radius-luminosity relation. In addition, the distribution is asymmetric with the prominent tail towards negative values. Michal Zajaček (Masaryk University) with Bozena Czerny (Polish Academy of Science) and their collaborators realized that such an effect can be attributed to dust causing absorption and scattering of UV as well as X-ray photons along the line of sight. Although the observed 58 quasars are located in the sky beyond the Milky Way dust clouds (see Figure 1), their nuclei are surrounded by numerous clouds with different geometries. In the recent study published in the Astrophysical Journal (Zajaček et al., 2023), Zajaček et al. showed explicitly that the extinction due to dust always contributes to the non-zero difference between the two luminosity distances inferred from quasar correlations, being either positive or negative, depending on whether X-ray or UV photons are more affected. Since the distribution peaks are positive for all the cosmological models, the extinction of X-ray emission from galactic nuclei appears to be more profound for most of the quasars than in the case of UV light.

Conclusion

Overall, the dust extinction impacts the UV/X-ray emission correlation more in comparison with the radius-luminosity relation since both UV and X-ray emission are affected in a different way, which makes it difficult to account for in the analysis. The presence of dust in the circumnuclear environment thus hinders the applicability of this relation in cosmology. On the other hand, the radius-luminosity relation appears to be still applicable for turning quasars into standard candles. Although the current constraints on cosmology inferred from the radius-luminosity relation are rather weak, the increasing number of reverberation-mapped quasars in the near future will likely lead to much tighter constraints with the prospects of determining which cosmological model is suited better for the description of the Universe.

Contact information

Dr. Michal Zajaček
Department of Theoretical Physics and Astrophysics
Masaryk University
Kotlářská 2
602 00 Brno
Czech Republic
email: zajacek@physics.muni.cz

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