Inverse Modeling Based on the Doppler Effect

Max Bazovsky, Schola Ludus, FMFI, University of Commenius, Slovakia,
maxbazovsky@yahoo.com

Abstract This contribution presents seven student-ready examples of inverse modeling of currently important cosmological factoids as clusters of small "mini-models" that are easy-to-understand at the high school level. Since they are thematically related, student-accessible and fun to reason about, the chosen grouping of models is very effective pedagogically. In fact it is hoped that this set of examples generate intense interest in the Doppler effect, in inverse modeling methods, and in their applications. Even more than in Earth-bound experiments, the data that we obtain from the stars and galaxies needs to be analyzed and interpreted. The seven examples show that evaluations must be made to choose from several possible inferences and/or interpretations. They all assume as prior knowledge (i) that the Doppler frequency shift equations can be solved for source velocity, (ii) that frequency/wavelength shifts can be read from the spectra of light, and (iii) the meaning of redshift and blueshift: (A) shows why dark matter is hypothesized, and describes why some alternative models are currently rejected, (B) Shows how the cosmological redshift can be interpreted either that the galaxies are simply receding, or that the whole space is expanding, (C) shows how inverse models of Lyman alpha forests corroborate that the universe is expanding, a conclusion that Edwin Hubble was reluctant to make in 1929, (D) shows how scientists predict space weather by "seeing" Sunspots through the Sun, (E) shows one popular method for finding extrasolar planets, (F) discusses the rotation rates of Mercury, and (G) discusses the differential rotation of the Sun using the Doppler effect.

The interpretation of data by the Doppler effect involves decision making based on incomplete information: inferring "distant" conditions of the source of radiation based on frequency shifts read from received spectra. For Doppler data obtained from many earthbound systems, the inference can be tested directly during model evaluation testing. In the cosmic case, however, the interpretation of spectral data by means of the Doppler effect calls for more careful considerations even when invoking the Copernican principle that the laws of the Universe are the same everywhere. I.e., the question remains whether the models are being applied outside of their limits of applicability; or whether the extreme conditions of distant stars/galaxies are known and/or considered fully, or whether the cognitive models are adequate. So, the interpretation is open to revision and improvement as tests of consistency and reasonableness are made. [1] gives a more general discussion of inverse modeling.

A Several Doppler effect studies of star motion imply discrepant inferences. E.g., the velocities of galactic orbits of stars as a function of their distance from their galaxy center are too high: they indicate that the mass inside the stars' orbits is much larger than the mass detected by telescopes. So, either Newton's laws of motion are not true "out there", or the law of gravity is not as simple as found by Newton, or corrected by Einstein[1]. Or, there is more matter there than we have found. In the 1930s Jan Oort, the discoverer of the Oort cloud, named the phenomenon, "missing mass", and Fritz Zwicky, named it "dark matter" – a mass that does not react with light! By plotting many "galaxy rotation curves" (of star velocity vs. radial distance) for many stars and galaxies, Vera Rubin showed that galaxies rotate with such high speeds that we do not know how they hold together against the centrifugal forces. Thus, the existence of dark matter must be inferred as long as other models continue to fail evaluation tests. No adequate alternative models are known at present. Modified Newtonian Dynamics, MOND, one such model assumes that for very small accelerations the, F=ma, is replaced by another equation. See [2] for more details on this whole paragraph, and on more insufficient alternative models.

B Einstein's general relativity theory predicts an expanding universe that began with the Big Bang explosion billions of years ago. Do your students know how this can be partially tested? If the galaxies are still all receding from each other, the Doppler effect predicts that light frequencies are redshifted. But, the force of gravity might have reversed the expansion. What is the actual case today? In 1929, US astronomer Edwin Hubble used the spectral analysis of light from each galaxy studied to verify the predicted redshift. This is the cosmological redshift of light from receding galaxies.

[1] Note for students: the law of gravity is relevant to restrain centrifugal forces, e.g., by equating the forces from the law of gravitation and from F = ma, we can determine the mass of the Sun from the orbital velocity of a planet and its radial distance from the Sun. This idea is used to determine total mass for stars orbiting their galactic center even though the situation is much more complicated by many stars inside the orbit of one star.

Hubble's data plot graph shows that, on the average, the redshift of a galaxy is proportional to its distance from our Sun. The main interpretation, using the Doppler effect, is that the Universe is expanding as predicted. Competing alternatives still exist, but they suffered a serious blow when new supporting evidence was discovered, as discussed next. See [3].

C Quasars are distant objects in the early universe that emit extremely powerful radiation with a component having a 121.6 nm rest wavelength, called the Lyman Alpha line after its discoverer. As the light travels from a distant galaxy it passes through intergalactic clouds of un-ionized hydrogen gas. These clouds absorb light at what is in their vicinity 121.6nm. But, according to B, when the light reaches such a cloud, it has been redshifted in proportion to the distance traveled. Sometimes the light passes hundreds of such clouds, and reaches Earth with a spectrum of progressively redshifted dips in intensity to the lower wavelength side of the emitted 121.6nm rest wavelength [4]. This information of cloud distribution in space is consistent with simulations of the evolving universe.

D Doppler frequency shift data shows that the Sun is a vibrating sound ball of plasma whose frequency modes can be measured by the Doppler effect. ESA/NASA have built the SOHO, Solar and Heliospherical Observatory satellite [5]. SOHO can make accurate Doppler shift measurements of millions of points, or patches of oscillating modes on the Sun's near side surface. The conditions observed on the near face of the Sun can be propagated backward to the far end of the Sun where any Sun spots will be indicated because their extremely high magnetic fields cause special conditions (faster propagation velocities) for the sound waves. Thus scientists detect Sunspots almost as they occur, predict high radiation to occur when a giant Sunspot round the Sun's horizon. Then affected operators will cancel space walks, safeguard high altitude electronics from intense radiation storms and divert polar flights to protect flyers from the heightened radiation.

E Doppler effect data analysis shows that some stars wobble back and forth along the line of sight (Earth-to-star). One interpretation is that a nearby heavy planet is causing the star to wobble about the barycenter (center of mass of the star system) according to Newton's third law, and to keep the center of constant. New telescope technology corroborates this, detecting a slight 1% drop in light intensity [6].

F Doppler effect measurements established the first reliable rotation rates estimates for Mercury. Being so close to the Sun, Mercury is difficult to observe long enough to establish its period visually. It is always less than 30 degrees from the Sun. Giovanni Schiaparelli's plausible but wrong inference from incomplete data was not corrected until Doppler radar data become available [7].

G Analysis of spectral data different latitudes of the Sun has established the differential rotation rates of the solar mass. Almost 400 years ago Galileo Galilei interpreted the motion of Sunspots to infer that the Sun rotates, and that the Sun is gaseous due to having rotation periods that are a function of latitude. The Doppler effect confirms this and provides much more information [5, 8].

In conclusion, we can see that the construction and/or selection of inverse models involves the creative technology of decision making – or of design methods as taught in Dutch high schools [9]. [9] describes the design process in a science and technology setting: - analyze the inputs, compose requirements, generate ideas, formulate proposed solutions, develop one or more of them, and finally, test the proposed solutions. For us, inputs = data; compose requirements = describe what is known and what this constraints/limits; ideas = ideas; proposed solution = proposed model; and tests = model verification tests (consistency with other facts, reasonableness, limitations, error bounds etc) as normally performed on all models to improve them and to increase confidence in their results.

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