

QUASAR ABSORPTION LINES

Volume 2: Astrophysics, Analysis, and Modeling

Quasar Absorption Lines is a comprehensive, detailed exposition on the science and analysis of quasar spectra in two volumes, for both aspiring and seasoned astronomers. This Volume 2: *Astrophysics, Analysis, and Modeling* describes atomic transitions of hydrogenic and multi-electron ions, the theoretical foundation and practical application of the Λ CDM cosmological model, and radiative transfer from cosmological sources. The theory of spectrographs and the mathematical formalism and quantitative analysis of spectral absorption lines and ionization breaks are treated in detail, including column density measurements, line deblending, and Voigt profile fitting. The philosophies, methods, and techniques of large absorption line surveys are presented, including methods for correcting incompleteness and for measuring accurate absorber population statistics. Gas physics, heating/cooling, and ionization are also covered, followed by detailed methods for undertaking multi-component, multiphase chemical-ionization modeling.

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Volume 2: Astrophysics, Analysis, and Modeling

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This work is devoted to the “quasar pioneers.”

John N. Bahcall — architect of the HST Quasar Absorption Line Key Project
Jacqueline Bergeron — establisher of the galaxy-absorber connection
John G. Bolton — finder of first extragalactic radio sources
E. Margaret Burbidge — early comprehensive spectroscopic studies of quasars
Geoffrey R. Burbidge — father of the quasar catalog
Cyril Hazard — perfecter of pin-point quasar positioning (lunar occultations)
C. Roger Lynds — conceiver of the Ly α forest, discoverer of BAL quasars
Thomas A. Matthews — co-discoverer of quasi-stellar objects
Allan R. Sandage — discoverer of quasi-stellar objects, first quasar absorption line
Wallace L. W. Sargent — father of the large, uniform, absorption line survey
Maarten C. Schmidt — first to decipher the redshifted spectrum of a quasar
Arthur M. Wolfe — founder of Damped Ly α absorber research

They forged astronomy into a whole new science and unlocked the modern view of the universe.

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Foreword

The second half of March 1963 will be remembered for two milestone events that took place just a few days apart. On Friday 22 March 1963 EMI released *Please Please Me*, the first album by The Beatles. Only eight days earlier, on 16 March, the premier scientific journal *Nature* had published a short paper by the Caltech astronomer Maarten Schmidt reporting the discovery of the first quasi-stellar radio source. Few people at the time probably realized the momentous consequences of these two unrelated events. The Beatles went on to revolutionize popular music with a prolific and all too short-lived output of original music which sixty years later has sold more than 500 million records. They transformed youth culture forever by elevating the younger demographic to a place of social prominence they refuse to relinquished. Similarly, Maarten Schmidt's discovery revolutionized extragalactic astronomy and motivated a huge amount of work, both observational and theoretical, that fundamentally changed our view of the Universe and that continues unabated to this day when the number of known quasars is well over a million.

In the early 1960s the objects which today we group under the generic label Active Galactic Nuclei, or AGN, were known from their radio emission. However, identification of these sources with objects that could be seen in photographs of the sky, i.e. their optical counterparts, was made difficult by the poor resolution of radio telescopes of the time. By accurately timing the occultation of the radio source 3C 273 (the 273rd entry in the Third Cambridge Catalogue of such sources) by the Moon from Australia, Cyril Hazard and collaborators were able to communicate precise sky coordinates to Maarten Schmidt who used the 200 inch optical telescope on Mount Palomar in California to record the spectrum of the 13th magnitude blue “star” that was closest to the radio position. The breakthrough by Maarten Schmidt was in realising that the emission lines recorded in his spectrum were those of the familiar Balmer series of hydrogen, but all shifted to longer wavelengths by a factor of 1.158, yielding a redshift of 0.158: this was not a star at all, but a member of a previously unrecognized class of unimaginably luminous astronomical objects! The genie was out of the bottle.

By 1965, only two years after Schmidt's discovery, redshifts as high as $z = 2$ were measured for radio quasars. And yet, their interpretation was a source of

much debate among astronomers. If quasar redshifts are due to the expansion of the universe — that is, if they are *cosmological* in the jargon of astronomy — they imply that their light has travelled huge distances on its way to us and this in turn leads to the conclusion that they are intrinsically very much brighter than any other source known at the time. Thus, 3C 273 evidently emits as much light as 200 galaxies like the Milky Way, while the brightest quasars known today are as luminous as ten thousand “normal” galaxies put together! This is astounding, especially when one considers that this huge output of energy is all produced within a tiny region of space, no bigger than our own solar system. Even back of the envelope calculations show that to produce this enormous energy density requires converting between 10 and 30 percent of the mass-energy locked in matter according to Einstein’s famous equation: $E = mc^2$. For comparison, stars like our Sun shine by converting a mere 0.7 percent of their mass into radiant energy.

In the early 1960s no mechanism was known that could turn matter into energy so efficiently and for some astronomers it was just too big a step to accept the paradigm-changing interpretations of cosmological quasar redshifts. However, all alternative interpretations put forward turned out to be rather contrived. Ultimately, influential papers by Ed Salpeter, Yakov Zel’dovich and Donald Lynden-Bell led to the modern view that the source of quasar luminosity is accretion onto supermassive black holes at the centres of galaxies. Such monstrous objects, with masses in excess of a billion stars like the Sun, are now understood to play a key role in the evolution of galaxies and have been the subject of many studies to probe physics under extreme conditions. Quasars have become a fundamental subject of astrophysics and cosmology. At the time of writing, more than 1, 250, 000 quasars have been cataloged, with the most distant being at a redshift greater than 10. The realisation that quasar redshifts are indeed cosmological, together with the discovery of the Cosmic Microwave Background also in the mid-1960s, spelt the demise of steady-state cosmologies for all but a minority of astrophysicists.

From the earliest days of the subject it was realized that, in addition to the broad and prominent emission lines that define their redshifts, the spectra of quasars exhibit many narrow *absorption* lines, mostly at redshifts lower than the emission redshift. Higher redshift quasars exhibit a markedly higher density of absorption lines. Unsurprisingly, at the time when the cosmological nature of quasar redshifts was being debated, the origin of these absorption lines was also being questioned: do they arise in gas and dust ejected by the quasar itself — the *intrinsic* interpretation — or do they mark the locations of absorbing clouds unrelated to the quasar and intersected by chance along our line of sight to the bright background source — the *intervening* hypothesis originally proposed by John Bahcall and Ed Salpeter?

The first view seemed quite reasonable: after all, the most luminous stars in our Galaxy are known to lose mass through stellar winds and many radio galaxies and quasars, including 3C 273, give rise to powerful jets. Furthermore, some (albeit a minority) of quasar absorption lines exhibit the P-Cygni profiles that are the tell-

tale signs of outflowing material. Conversely, the intervening hypothesis seemed to require an excess of galaxies to populate the space between quasars and us in order to reproduce the number density of absorbers. However, most quasar absorption lines are intrinsically very narrow; if they were ejected, some mechanism would be required to accelerate the gas to a significant fraction of the speed of light while maintaining a very low internal velocity dispersion — a highly unlikely combination.

The controversy generated by these two differing points of view lasted for nearly two decades and, like analogous examples in the history of science, was at times heated and intense. Quoting from the first paragraph of the Introduction of the 1981 Annual Review of Astronomy and Astrophysics by Ray Weymann, Bob Carswell and Malcolm Smith entitled “Absorption Lines in the Spectra of Quasistellar Objects:”

*“We speculate that over the last decade more observing time on large telescopes has been spent on spectroscopy of QSO absorption lines than on any other program. Partly this reflects a desire to resolve the intense controversy that has arisen over the origin of QSO absorption lines, but it also reflects the realization that when the origins of these lines are fully understood, an enormous amount of information concerning the environment of QSOs and uncondensed intervening gas becomes available.”*¹

Eventually, consensus gravitated towards the intervening interpretation, bolstered by two key findings. The first was the *ex post facto* identification of low-redshift galaxies at the same redshifts as the absorption lines present in the spectrum of a quasar, proving that the absorption cross-section of galaxies could be much larger than their visible size (in such cases the absorbing galaxy and the quasar were separated by small angular distances on the sky and yet were at very different redshifts). Teams led by Jacqueline Bergeron and Alec Boksenberg were pioneers in these endeavors. The other nail in the coffin of the intrinsic hypothesis was an influential paper published in 1980 by Wal Sargent, Peter Young and colleagues providing the first rigorous analysis of the statistics of the multitude of absorption lines seen at shorter wavelength than the emission Lyman alpha line of neutral hydrogen. Almost ten years earlier Roger Lynds had proposed that these features are mostly individual Lyman alpha absorption lines; Sargent’s paper showed them to be entirely consistent with the intervening hypothesis and very unlikely to be explained as being ejected from the quasars whose spectra the authors had acquired. These breakthroughs were in large part made possible by the availability of a new, high resolution, low noise detector, the Image Photon Counting System developed at University College London by Boksenberg’s research group, far superior in recording faint astronomical signals than the photographic emulsions that had mostly been used previously.

¹ Here the word quasar has been replaced by QSO; although the two terms have different origins they are often used interchangeably.

Free from drag of scientific controversy, the topic of quasar absorption lines was free to fulfil its huge potential highlighted in the opening sentence of the 1981 review. And what a journey has this subject witnessed! Over the last 40 years, the technique of quasar absorption lines has been used to tackle some of the most fundamental questions in extragalactic astronomy and cosmology. The following account serves to give a broad view of the multitude of applications of the tool of absorption line spectroscopy, although of necessity it focuses on a few illustrative examples.

In the early days of the subject, it was customary to make a distinction between the absorption lines found, respectively, at longer and shorter wavelengths than the emission Lyman alpha line. The former could be readily identified as the strongest atomic transitions of the most common elements of the Periodic Table, grouped into discrete *absorption systems*; while the latter, more numerous than the former by a factor of 50, could not and were therefore presumed to be individual Lyman alpha absorption lines — after all hydrogen is the most abundant element in the cosmos and Lyman alpha is its strongest spectral feature. The only way we know to synthesize elements of the Periodic Table is through nuclear fusion in the interiors of stars; it therefore seemed reasonable to associate the former, the so-called “metal” absorption systems² with intervening galaxies, even if the galaxies themselves were too distant and too faint to be recognized in direct images. On the other hand, the plethora of individual lines which came to be known as the “Lyman alpha forest” appeared to have few, if any, corresponding metal lines at the same redshifts and were therefore interpreted as absorption by diffuse clouds of gas in a near-pristine intergalactic medium (IGM).

As the subject advanced in the 1980s and 1990s, it came to be realized that this was an overly simplistic view. With the aid of increasingly sophisticated computer simulations of the growth of structure in the Universe, a more holistic picture was developed in which all quasar absorption lines are seen as a map of density fluctuations along the line of sight between a quasar and us. The highest densities encountered are the sites of galaxy formation, while lower density volumes harbour the warm, photoionized intergalactic medium which gives rise to absorption in the Lyman alpha forest. However, for our present purposes, it may be convenient to use the early, rather black-and-white, working model that made a distinction between metal lines from galaxies and the Lyman alpha forest from the intergalactic medium.

Considering first the metal lines, one of their primary applications has been to study the physical conditions of the gaseous halos of galaxies over cosmic times. How extensive are these halos? What is their composition? How are they generated and maintained? And how do all these properties vary with look-back time and how do they depend on the properties of the visible parts of galaxies, i.e. galaxy morphology? Over time, these studies have built up an overall framework of the so-called

² For simplicity, astronomers use the term *metals* to denote all chemical elements heavier than helium, irrespectively of their solid state properties.

cosmic baryon cycle, the flow of multi-phase gas that accretes to galaxies from the IGM, forms stars and is subsequently partly recycled through the interstellar and circumgalactic media by galaxy-scale outflows driven by supernova explosions. As emphasized in the excellent 2021 Annual Review of Astronomy and Astrophysics by Celine Péroux and Chris Howk, we can now probe the global evolution of baryons, metals, and dust over 90 percent of cosmic time, mostly thanks to absorption line studies.

The column densities of neutral hydrogen exhibited by quasar absorbers span more than ten orders of magnitude. At the upper end of this distribution are the so-called “damped Lyman alpha” systems (DLAs); Art Wolfe at the University of Pittsburgh was the first to highlight their importance as probes of galaxy evolution in a prescient paper published in 1986. It was recognized soon after that these DLAs are the most suitable environments where it may be possible to obtain precise measures of the chemical composition of the gas, including gas that has undergone minimal enrichment through successive cycles of stellar nucleosynthesis. Such gas is rare in our present-day cosmic environment, but with some effort it can be found at earlier times (i.e. at high redshifts); the many studies that have proliferated over the last thirty years or so have given us precious clues to the early populations of stars that first shone in the Universe.

Perhaps an even more spectacular outcome of these chemical studies has been the determination of the primordial abundance of deuterium with percent precision, most recently by Ryan Cooke from Durham University and his collaborators. All deuterium was assembled from protons and neutrons in the first few minutes after the Big Bang; subsequently D has been consumed every time gas has condensed into stars. The primordial ratio of deuterium to hydrogen depends sensitively on the density of ordinary matter (baryons) in the Universe, which astronomers denote with the symbol Ω_b ; as pointed out by David Schramm from the University of Chicago, deuterium is the “baryometer” of choice. As early as 1976, Thomas Adams, also from Chicago, proposed that quasar absorption lines could be used to measure the primordial D/H ratio, but this promise was not fulfilled until twenty years later, with the advent of a new class of very large optical telescopes, with the light collecting power of 8–10 m diameter primary mirrors. Apart for the sheer allure of being able to probe physical processes that took place so early in the history of our Universe, well beyond the photon curtain presented by the release of the cosmic microwave background some 375,000 years later, what is astonishing about these deuterium measurements is the exquisite agreement with our other source of information on the value of Ω_b : the temperature fluctuations on the sky of the CMB, as measured by the ESA Planck satellite. Such concordance is an outstanding success of the Standard Model of particle physics as well as an indisputable confirmation of the validity of Big Bang cosmologies.

And indeed, quasar absorption lines have provided some of the most interesting and diverse tests of the Standard Model. Absorption lines from the fine structure

levels of atoms, ions and molecules have been examined to check on the expected redshift evolution of the CMB temperature — CMB photons were important in determining the level populations at different epochs. Plans are afoot to attempt to detect the expansion of the Universe in action, as it were, by a very sensitive measure of the change in redshift with time of the myriad of quasar absorption lines to be recorded with the next generation of giant telescopes. Teams from Australia and Italy, among others, have used the wavelengths of quasar absorption lines to look for time variations of some of the fundamental constant of physics, such as the fine-structure constant and the proton-to-electron mass ratio, acting on a far-sighted paper by Art Wolfe proposing such tests as early as 1976, again well before they could be feasibly carried out. Such variations, if found, would discriminate between possible extensions of the Standard Model which have been proposed.

I could carry on for a long time, but that is not the purpose of a foreword. All of the above applications, as well as many others, are considered in much detail and explained lucidly in these marvelous monographs by Professor Churchill, which are a long awaited update on the only other titles in this subject of which I am aware: *Quasi-Stellar Objects*, which is a sorting out of the nascent science of quasars by Geoffrey R. and E. Margaret Burbidge published nearly sixty years ago, and a follow-up summary *Quasar Astronomy* by Daniel W. Weedman published nearly forty years ago. And yet, strictly speaking, the story of the last 60 years of quasars and their absorption spectra accounts for just the first half of Professor Churchill's extraordinary two book set. The second half deals first with the core knowledge required to make sense of it all, from the underlying atomic physics to cosmology and to the physics of the interaction of light with matter. This is followed by a description of the most important aspects of the instrumentation and techniques that have been used in the acquisition and analysis of absorption line data. Finally, the reader will learn about the thermodynamics of the gas that gives rise to the absorption lines, so that from the data we collect we may be able to deduce the physical properties of the absorbers. To collect all this encyclopedia of relevant knowledge under one assemblage has never been attempted before and is the phenomenal achievement of these two volumes. Students and experts in the field will find them an endless source of information and a much used reference text for many years to come.

Max Pettini
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April 2025

Preface Volume 2

At the time of this writing, it has been roughly 65 years since the discovery of quasars.³ In those first few years, there were several monikers for these mysterious lights in the sky: quasi-stellar objects (QSOs) and quasi-stellar radio sources (QSSs) were the two most common. For the strongest radio sources, the latter were sometimes abbreviated QSRs. It was March 1963 when the *Nature* paper reporting the correct interpretation of the redshifted emission lines in the spectrum of QSS 3C 273 was published by Caltech astronomer Maarten Schmidt.

A few short years later, in January 1967, the first book to summarize these objects was published. Written by the pioneering team Geoffrey R. and E. Margaret Burbidge, it was simply titled *Quasi-Stellar Objects*, totaled 235 pages, and explored the early discovery and understanding of quasars. It was not until shortly after the quarter-century anniversary of Schmidt's landmark paper that a second book was published — 1986's summary by Daniel W. Weedman titled *Quasar Astronomy*. Weedman's brief 205-page book summarized what was known about quasars up to that point in time (their physical characteristics, evolution, and distribution in the Universe). It also described observational techniques, and provided a summary of unanswered questions (which were many). The material focused on the observational aspects of quasar astronomy rather than on the astrophysics and theory. And, as Weedman foresaw, the subfield “quasar absorption lines” has since blossomed into one of the most impactful areas of study in all the sciences.

Examining the ~ 60 -year expanse since *Quasi-Stellar Objects* and the ~ 40 -year gulf since *Quasar Astronomy*, we find no similar offering. In the interim, quasar astronomy exploded in scope; four decades of technological advancements in astronomical facilities and exponential growth in computational power has fueled a revolution in methods and scientific understanding. A modern text on the subject is well overdue; but the amount of material to cover feels about 10,000-fold compared to Weedman's world of the 1980s. Furthermore, the astrophysical theory at the foundation of the analysis of these absorption lines had not been covered in the previous books.

³ An optical spectrum of the radio source 3C 48 was obtained in December 1960 by A. Sandage and collaborators.

For these reasons, a modern comprehensive overview requires much more than a few hundred pages. Indeed, a two-volume set has been required:

Volume 1

Volume 1 of this two-volume set, which comprised the first three PARTS of six, covered some key milestones of the historical development of modern quasar science with much of the emphasis on intervening absorption lines. As much as possible, scientific discoveries were presented in chronological order. This is because science is like an ogre, and as we all learned from Shrek, “ogres are like onions.” Scientific knowledge is revealed an onion layer at a time and, one could argue, should be presented one layer at a time. Why? — so as to not only inform the reader what was learned *after* 60+ years of quasar absorption line science, but to encourage the reader to also thoughtfully experience the journey. Scientific progress is fundamentally a shared cultural experience.

PART ONE focused on how the technique of quasar evolved into its modern form and essentially revolutionized the science of astronomy. This included an overview of the cosmic context of quasar absorption line studies in terms of the major eras and epochs of the Universe. An executive summary of the key quantities typically measured from absorption line surveys was provided; these included measurements such as the redshift path density, column density distribution functions, the cosmic mass density of various ions, and other absorber population statistics. In addition, modern methods, such as down-the-barrel techniques, spectral stacking techniques, galaxies-probing-galaxies experiments, and absorption toward GRBs, etc., were summarized.

PART TWO focused on the observations and statistics of intervening absorbers, which were segregated into low-, intermediate-, and high-ionization systems. A review of the evolution of the Ly α forest, Lyman-limit, and damped Ly α absorbers was followed by a deep dive into the deuterium abundance and its impact on Big Bang nucleosynthesis. Then, 21-cm absorption studies were reviewed, followed by comprehensive reviews of each of the commonly studied metal-line absorbers.

PART THREE focused on galaxy halos, gas around galaxies, and AGN/quasars. The topics concentrated on the CGM-galaxy connection, i.e., the empirical characterization of the baryon cycle in terms of what people can actually measure as astronomically remote observers. The connection between galaxies and their dark matter halos was presented, followed by the observational findings from studies of galaxy-absorber pairs. Group and cluster environments were also addressed. Finally, the taxonomy of AGN/quasar spectra was summarized, followed by a discussion of black hole accretion and line-driven radiative accelerated winds, such as the famous broad absorption lines (BALs).

Volume 2

This is **Volume 2**, which comprises the final three PARTS of this work. This volume focuses on the physics of absorbers, cosmology, radiative transfer, spectroscopic data and analysis, and tools for analyzing absorbers.

PART FOUR focuses on the atomic physics of absorption lines. It begins with hydrogenic ions and progresses to multi-electron ions, covering absorption cross sections, oscillator strengths, forbidden and permitted transitions, ionization potentials, etc. Also covered are iso-electron configurations and how they yield “spectroscopic families” of ions. Shifting to the larger frame of reference, the formalism of the Λ CDM cosmology and the cosmological redshift are summarized. Finally, radiative transfer in the cosmological context is presented.

PART FIVE focuses on the details of spectrographs, spectroscopic data, and the analysis of spectroscopic data. This is where measurements such as equivalent width, column density, and velocity spread are reviewed. Also covered are Gaussian and Voigt profile fitting of kinematically complex high-resolution absorption profiles.

PART SIX, is divided into two halves. The first half covers the macro and micro physics of gaseous systems. The second half discusses the chemical-ionization modeling of absorbers. This latter material is probably the most challenging as it requires physical intuition, and this physical intuition requires experience. So, when one is learning how to model absorbers, the early learning curve is very steep.

Throughout both volumes, I have attempted to provide a comprehensive set of references⁴ on the subject, both historical and modern. I apologize to the authors of many excellent papers and important works that have not been represented herein. Such omissions do not reflect, in any way, a diminutive or critical opinion on my part of the works in question.

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⁴ This work has made extensive use of (1) NASA’s Astrophysics Data System Bibliographic Services, (2) the National Institute of Standards and Technology (NIST) database, and (3) the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.