The 21 cm line of Hydrogen and its Role in Astrophysics - A Review

***Dr.Shivaraj Gadigeppa Gurikar. Asst Professor of Physics. Govt First Grade College, Yelburga.**

Abstract

This paper studies the hydrogen line, 21-centimeter line or H I line is the electromagnetic radiation spectral line that is created by a change in the energy state of neutral hydrogen atoms. Hydrogen is the most abundant element in the interstellar medium (ISM), but the symmetric H2 molecule has no permanent dipole moment and hence does not emit a detectable spectral line at radio frequencies. Neutral hydrogen (HI) atoms are abundant and ubiquitous in low-density regions of the ISM. They are detectable in the 21 cm (10=1420405751 MHz) hyperfine line. Two energy levels result from the magnetic interaction between the quantized electron and proton spins. When the relative spins change from parallel to antiparallel, a photon is emitted.wavelength emitted by cold, neutral, interstellar hydrogen atoms. The hydrogen atom is composed of a positively charged particle, the proton, and a negatively charged particle, the electron. These particles have some intrinsic angular momentum called spin. (However, this spin is not an actual physical rotation; it is, rather, a quantum mechanical effect.) When the spins of the two particles are antiparallel, then the atom is in its lowest energy state. When the spins are parallel, the atom has a tiny amount of extra energy. In the very cold space between the stars, the interstellar hydrogen atoms are at a state of lowest possible energy. Collisions between particles, however, can at times excite some atoms (which makes the spin of the particles parallel), giving them a tiny amount of energy.

According to the rules of quantum mechanics, such atoms radiate their acquired energy in the form of low-energy photons that correspond to a wavelength of 21 centimetres, or a frequency of 1,420 megahertz. This radio radiation was theoretically predicted by the Dutch astronomer H.C. van de Hulst soon after the end of World War II and was experimentally detected by American physicists Harold Ewen and Edward Purcell at Harvard University in 1951. Since that time, 21-centimetre hydrogen emission has come to play a vital role in the study of the Milky Way Galaxy, because it readily penetrates the clouds of interstellar dust particles that obstruct optical observations deep into the galactic centre.About 99% of the interstellar medium is gas with about 90% of it in the form of hydrogen (atomic or molecular form), 10% helium, and traces of other elements. At visible wavelengths, however, dust has a greater effect on the light than the gas. The presence of interstellar gas can be seen when you look at the spectral lines of a binary star system. Among the broad lines that shift as the two stars orbit each other, you see narrow lines that do not move. The narrow lines are from much colder gas in the interstellar medium between us and the binary system.

Key words: photon emitted, wavelength, hydrogen gas, molecular form, spectral lines

Introduction

The hydrogen gas is observed in a variety of states: in ionized, neutral atomic, and molecular forms. H II Regions H II regions are regions of hot (several thousand K), thin hydrogen emission nebulae that glow from the fluorescence of hydrogen atoms. The roman numeral "II" of H II means that hydrogen is missing one electron. A He III nebula is made of helium gas with two missing electrons. A H I nebula is made of neutral atomic hydrogen. Ultraviolet light from hot O and B stars ionizes the surrounding hydrogen gas. When the electrons recombine with the protons, they emit light mostly at visible wavelengths, and primarily at a wavelength of 656.3 nanometers (giving the hydrogen emission nebulae their characteristic red color). In this conversion of the ultraviolet energy, each ultraviolet photon produces a visible photon. The temperature of the stars causing the nebula to fluoresce can be estimated from this even though the O and B stars are hidden inside the nebula. Fluorescent light bulbs operate on the same basic principle except they use mercury vapor to produce ultraviolet light. The ultraviolet light is then converted to visible light by the phosphor layer on the inside of the glass bulb. Below is a famous H II region called the Orion Nebula. It is the fuzzy patch you can see in the sword part of the Orion constellation. It is the closest large star formation factory to us and is explored in more detail in the stellar evolution chapter. Selecting the image will bring up a close-up of the heart of the nebula in another window showing the four hot "Trapezium" stars (four O and B stars making a trapezoid figure) at the center of each of the images by AAO and HST. Another large H II region is the Lagoon Nebula in the constellation Sagittarius. The ionized hydrogen emits light in the visible band as the electrons recombine with the protons and the neutral atomic and molecular hydrogen emits light in the radio band of the electromagnetic spectrum.

It is about 5000 light years away and spans 90 by 40 arc minutes in our sky. Converting the angular size to a linear size, the Lagoon Nebula is about 130 by 60 light years in extent (the Orion Nebula is only 29 by 26 light years in size). The complex interaction of the intense radiation from the hot stars lighting up the nebula, varying densities of the gas and dust, and temperature differences creates twisted, turbulent features in the nebula that have been explored by the Hubble Space Telescope. Selecting the image will bring up the high-resolution image of the heart of the Lagoon Nebula from the Hubble Space Telescope in another window. Next to the Lagoon Nebula on our sky (but closer to us in space) is the Trifid Nebula, so-called because of the dust lanes that trisect the H II region behind them. The image below is nice one to illustrate the three types of nebulae: the red H II region behind a dark dust nebula (showing the effect of the extinction of light) and next to them a blue reflection nebula (showing the preferential scattering of shorter wavelengths). the Trifid Nebula O and B-type stars are only found in regions of star formation because they are young stars. These hot, very luminous stars do not live long enough to move away from where they were formed. Since stars form in clusters, where O and B stars are found, there are sure to be smaller, lower-mass stars still forming.

The spectra of H II regions are much simpler than star spectra so they are easier to decipher. The composition and conditions inside the H II regions are easier to determine and understand than for stars, so H II regions provide a valuable tool for understanding the history of star formation in a galaxy. H II regions also provide a convenient way to map the structure of a galaxy because they are so large and luminous. In our galaxy the H II regions are distributed in a spiral pattern. The best wavelengths to use to map the distribution of hydrogen, however, are in the radio band.

Objective:

This paper seeks to review the 21cm line of hydrogen and its role in astrophysics, According to that relation, the photon energy of a 1,420,405,751.7667 Hz photon is ≈5.87433 μeV.

The Hydrogen 21-cm Line theoretical framework

Most of the hydrogen gas is not ionized because O and B stars are rare. Also, energy in the form of radio passes easily through dust. 21-cm Line Radiation Most of the hydrogen gas in the interstellar medium is in cold atomic form or molecular form. In 1944 Hendrik van de Hulst predicted that the cold atomic hydrogen (H I) gas should emit a particular wavelength of radio energy from a slight energy change in the hydrogen atoms. The wavelength is 21.1 centimeters (frequency = 1420.4 MHz) so this radiation is called 21-cm line radiation. The atomic hydrogen gas has temperatures between 100 K to about 3000 K. Most of the hydrogen in space (far from hot O and B-type stars) is in the ground state. The electron moving around the proton can have a spin in the same direction as the proton's spin (i.e., parallel) or spin in the direct opposite direction as the proton's spin (i.e., anti-parallel). The energy state of an electron spinning anti-parallel is slightly lower than the energy state of a parallel-spin electron. Remember that the atom always wants to be in the lowest energy state possible, so the electron will eventually flip to the anti-parallel spin direction if it was somehow knocked to the parallel spin direction.

The energy difference is very small, so a hydrogen atom can wait on average a few million years before it undergoes this transition. how hydrogen produces 21-cm line radiation Even though this is a RARE transition, the large amount of hydrogen gas means that enough hydrogen atoms are emitting the 21-cm line radiation at any one given time to be easily detected with radio telescopes. Our galaxy, the Milky Way, has about 3 billion solar masses of H I gas with about 70% of it further out in the Galaxy than the Sun. Most of the H I gas is in disk component of our galaxy and is located within 720 light years from the midplane of the disk. What's very nice is that 21-cm line radiation is not blocked by dust! The 21-cm line radiation provides the best way to map the structure of the Galaxy. Using 21-cm line radiation to Map the Galaxy The intensity of the 21-cm emission line depends on the density of the neutral atomic hydrogen along the line of sight. Atomic hydrogen all along the line of sight will contribute to the energy received. You need a way to determine the distance to each clump of hydrogen gas detected. Then when you observe the Galaxy in different directions, you can get a three-dimensional picture of the Galaxy. Using the rotation curve, the doppler-shifted radio emission can be converted into distances to the hydrogen clouds. The rotation curve is a plot of the orbital velocity of the clouds around the galactic center vs. their distance from the Galaxy center. The term "rotation" in this context refers to the motion of the galactic disk as a whole---the disk made of stars and gas clouds appears to spin. The gas clouds are assumed to move in the plane of the disk on nearly circular orbits. Jan Oort (lived 1900--1992) found in 1927 that stars closer to the galactic center complete a greater fraction of their orbit in a given time than stars farther out from the center. This difference in the angular speeds of different parts of the galactic disk is called differential rotation.

The line center frequency derivation

$$\nu_{10} = \frac{3}{8} g_I \left(\frac{m_e}{m_p}\right) \alpha^2 (R_M c) \approx 1420.405751 \text{ MHz} \quad (7E1)$$

where $g_I \approx 5.58569$ is the ***nuclear g-factor*** for a proton, $\alpha \equiv e^2/(\hbar c) \approx 1/137.036$ is the dimensionless ***fine-structure constant***, and $R_M c$ is the hydrogen Rydberg frequency (Eq. 7A2).

The 1420 MHz HI line is an extremely useful tool for studying gas in the ISM of external galaxies and tracing the large-scale distribution of galaxies in the universe because HI is detectable in most spiral galaxies and in some elliptical galaxies.

The observed center frequency of the HI line can be used to measure the radial velocity *V*r of a galaxy. The radial velocity of a galaxy is the sum of the recession velocity caused by the uniform Hubble expansion of the universe and the "peculiar" velocity of the galaxy. The radial component of the peculiar velocity reflects motions caused by gravitational interactions with nearby galaxies and is typically $\sim$200 km s−1 in magnitude. The Hubble velocity is proportional to distance from the Earth, and the ***Hubble constant*** of proportionality has been measured as $H_0 \approx 72$ km s−1 Mpc−1. If the radial velocity is significantly larger than the radial component of the peculiar velocity.

HI frequency can be used to estimate the *Hubble distance*

$D \approx v_r / H_0$ to a galaxy.

Example: Use the HI emission-line profile below of the galaxy UGC 11707 to estimate its Hubble distance $D \approx v_r / H_0$ if $H_0 \approx 72$ km s−1 Mpc−1. If the radial velocity $v_r \ll c$, then the nonrelativistic Doppler formula can be used to calculate *v*r from the observed line frequency ν:

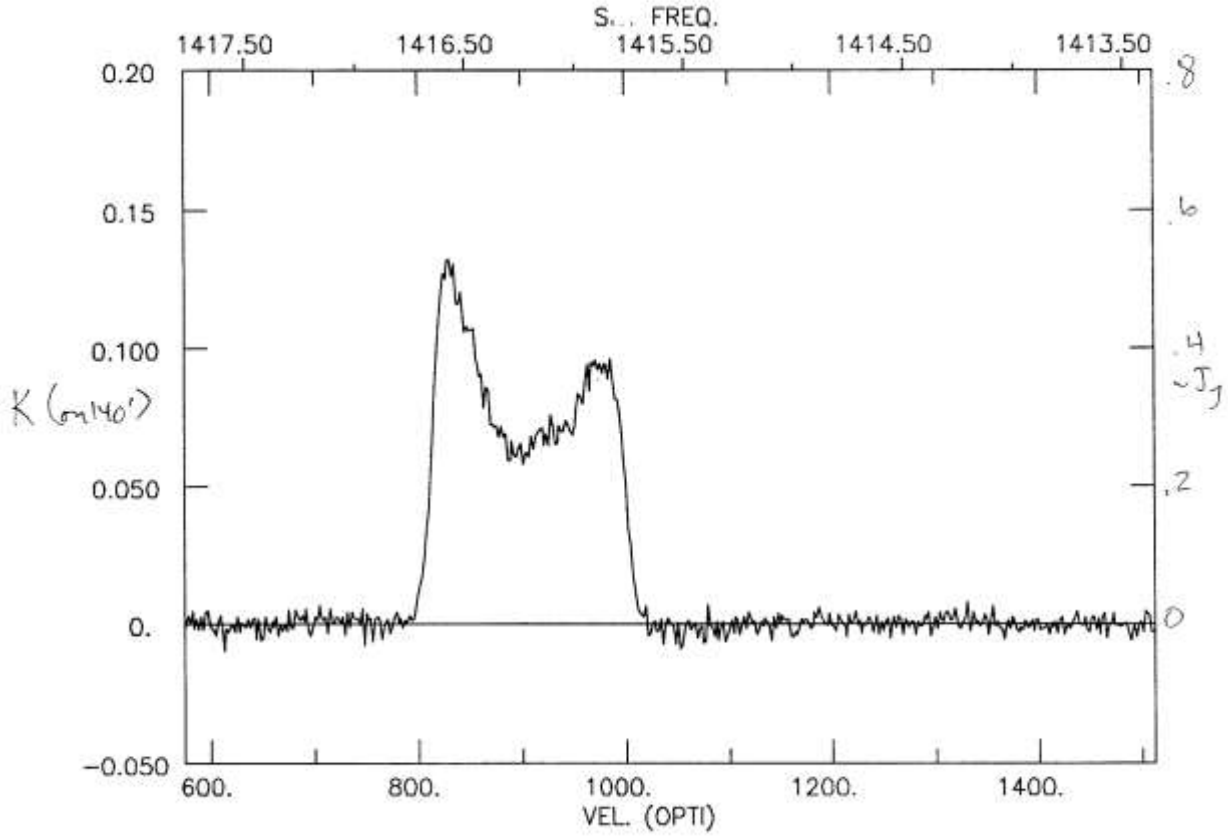
$\frac{v_r}{c} \approx \frac{\nu_0 - \nu}{\nu_0}$,

where $\nu_0 \approx 1420.4$ MHz is the rest-frame frequency. This equation yields what is known as the ***radio velocity*** because radio astronomers measure frequencies, not wavelengths. Optical astronomers measure wavelengths, not frequencies, so the ***optical velocity*** is defined by

$\frac{v_r}{c} \approx \frac{\lambda - \lambda_0}{\lambda_0}$.

Beware of this "gotcha": the optical and radio velocities are not exactly equal. Occasionally an observer confuses them, fails to center the observing passband on the correct frequency, and ends up with only part of the HI spectrum of a galaxy.

Since λ=21 cm is such a long wavelength, many galaxies are unresolved by single-dish radio telescopes. For example, the half-power beamwidth of the 100 m GBT is about 9 arcmin at λ=21 cm. Thus a single pointing is sufficient to obtain a spectral line representing all of the HI in any but the nearest galaxies.



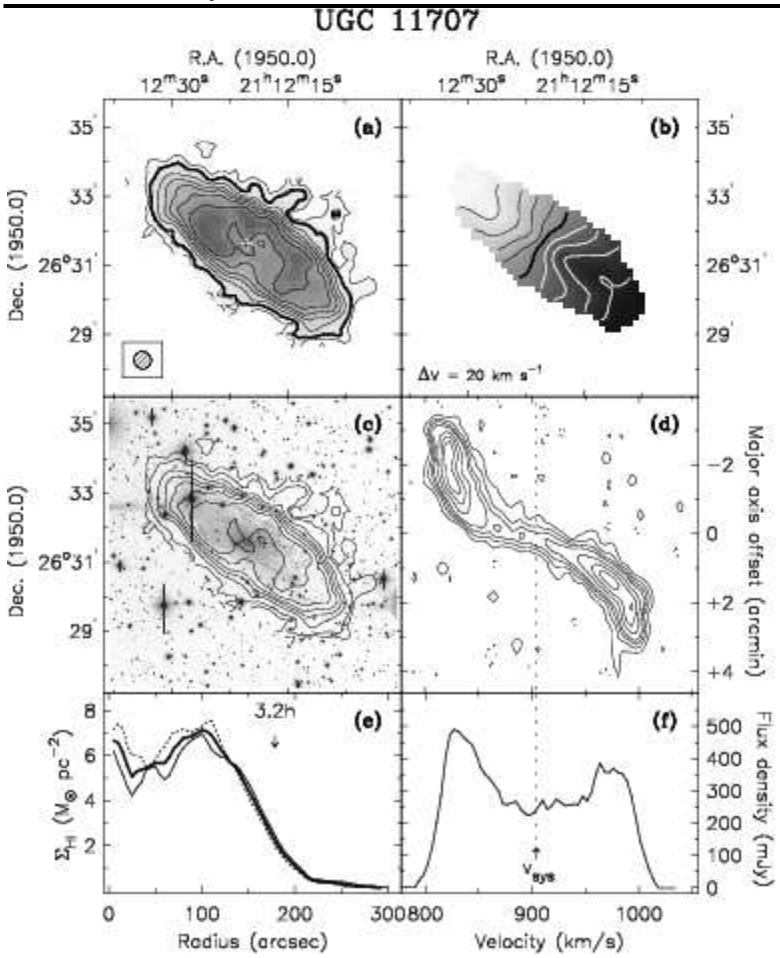
This integrated HI spectrum of UGC 11707 obtained with the 140-foot telescope (beamwidth ≈20 *arcmin) shows the typical two-horned profile of a spiral galaxy.*

For UGC 11707, the line center frequency is $\nu \approx 1416.2$ MHz, so

$$v_r \approx c\left(1-\frac{\nu}{\nu_0}\right) \approx 3\times 10^5 \text{ km s}^{-1}\left(1-\frac{1416.2 \text{ MHz}}{1420.4 \text{ MHz}}\right) \approx 890 \text{ km s}^{-1}$$

$$D \approx \frac{v_r}{H_0} = \frac{890 \text{ km s}^{-1}}{72 \text{ km s}^{-1} \text{ Mpc}^{-1}} = 12.4 \text{ Mpc}$$

$$\left[\left(\frac{v}{\text{cm s}^{-1}}\right)\left(\frac{\text{km s}^{-1}}{10^5 \text{ cm s}^{-1}}\right)\right]^2 =$$



UGC 11707 is a relatively low-mass spiral galaxy.

This "total" mass is really only the mass inside the radius sampled by detectable HI. Even though HI extends beyond most other tracers such as molecular gas or stars, it is clear from plots of HI rotation velocities versus radius that not all of the mass is being sampled, because we don't see the Keplerian relation $v_r \propto r^{-1/2}$ which indicates that all of the mass is enclosed within radius r. Most ***rotation curves***, one-dimensional position-velocity diagrams along the major axis, are *flat* at large r, suggesting that the enclosed mass $M \propto r$ as far as we can see HI. The large total masses implied by HI rotation curves provided some of the earliest evidence for the existence of cold dark matter in galaxies.

Epoch of Reionization (EOR)

Most of the normal matter in the early universe was fully ionized hydrogen and helium gas, plus trace amounts of heavier elements. This smoothly distributed gas cooled as the universe expanded, and the free protons and electrons recombined to form neutral hydrogen at a redshift $z \approx 1091$ when the age of the universe was about 3.8×10^5 years. The hydrogen remained neutral during the "dark ages" prior to the formation of the first ionizing astronomical sources, massive ($M > 100 M_\odot$) stars, galaxies, quasars, and clusters of galaxies, by gravitational collapse of overdense regions. These astronomical sources gradually started reionizing the universe when it was several hundred million years old ($z \sim 10$) and completely reionized the universe by the time it was about 10^9 years old ($z \sim 6$). This era is called the ***epoch of reionization***.

The highly redshift HI signal was uniform prior to the first reionization. The signal developed structure on angular scales up to several arcmin as the first sources created bubbles of ionized hydrogen around them. As the bubbles grew and merged, the HI signal developed frequency structure corresponding to the redshifted HI line frequency. The characteristic size of the larger bubbles reached about 10 Mpc at $z \sim 6$, corrresponding to HI signals having angular scales of several arcmin and covering frequency ranges of several MHz. These the HI signals encode unique information about the formation of the earliest astronomical sources.

The HI signals produced by the EOR will be very difficult to detect because they are weak (tens of mK), relatively broad in frequency, redshifted to low frequencies (< 200 MHz) plagued by radio-frequency interference, and lie behind a much brighter (tens of K) foreground of extragalactic continuum radio sources. Nonetheless, the potential scientific payoff is so great that several groups around the world are developing instruments to detect the HI signature of the EOR. One such instrument is the Precision Array to Probe the Epoch of Reionization, a joint project of UC Berkeley, the NRAO, and the University of Virginia that has placed a test array in Green Bank, WV and will soon construct a science array in western Australia, where there is very little RFI.

Conclusion

The Milky Way has about 2.5 billion solar masses of molecular gas with about 70% of it in a ring extending from 13,000 to 26,000 light years from the center. Not much molecular gas is located at 4,900 to 9,800 light years from the center but about 15% of the total molecular gas mass is located within 4,900 light years from the center. Most of the molecular clouds are clumped in the spiral arms of the disk and stay within 390 light years of the disk mid-plane. Molecular Hydrogen and Carbon Monoxide Connection Molecular hydrogen H2 does not produce radio emission.

It produces absorption lines in the ultraviolet. However, the gas and dust become so thick in a molecular cloud that the ultraviolet extinction is too large to accurately measure all of the H2 in the interior of the cloud. Fortunately, there is evidence of a correlation between the amount of CO and H2, so the easily detected CO radio emission lines (at 2.6 and 1.3 mm) are used to infer the amount of H2. The CO emission is caused by H2 molecules colliding with the CO molecules. An increase in the density of the H2 gas results in more collisions with the CO molecules and an increase in the CO emission. Another nice feature of the CO radio emission is that its wavelength is small enough (about 100 times smaller than 21-cm line radiation) that even medium-sized radio telescopes have sufficient resolution to map the distribution of the molecular clouds. The higher resolution of large radio telescopes can be used to probe the structure of individual molecular clouds. There is some controversy about how the molecules are clumped together in the clouds. Is one gas cloud actually made of many smaller gas clouds? There is some evidence that indicates that 90% of the H2 is locked up in 5000 giant molecular clouds with masses greater than 105 solar masses and diameters greater than 65 light years. The largest ones, with diameters greater than 160 light years, have more than a million solar masses and make up 50% of the total molecular mass. Other studies indicate that the giants are actually made of smaller clouds grouped together into larger complexes.

References

1. Gilbert, Jimmie; Gilbert, Linda (2005), Elements of Modern Algebra, Thomson Brooks/Cole, ISBN 978-0-534-40264-8
2. Lang, Serge (2002), Algebra, Graduate Texts in Mathematics, 211 (Revised third ed.), New York: Springer-Verlag, ISBN 978-0-387-95385-4, MR 1878556
3. Sethuraman, B. A. (1996), Rings, Fields, Vector Spaces, and Group Theory: An Introduction to Abstract Algebra via Geometric Constructibility, Berlin, New York: Springer-Verlag, ISBN 978-0-387-94848-5
4. Whitehead, C. (2002), Guide to Abstract Algebra (2nd ed.), Houndmills: Palgrave, ISBN 978-0-333-79447-0
5. W. Keith Nicholson (2012) Introduction to Abstract Algebra, 4th edition, John Wiley & Sons ISBN 978-1-118-13535-8 .
6. John R. Durbin (1992) Modern Algebra : an introduction, John Wiley & Sons
7. Artin, Michael (1991), Algebra, Prentice Hall, ISBN 978-0-89871-510-1
8. Blass, Andreas (1984), "Existence of bases implies the axiom of choice", Axiomatic set theory (Boulder, Colorado, 1983), Contemporary Mathematics, 31, Providence, R.I.: American Mathematical Society, pp. 31–33, MR 0763890
9. Brown, William A. (1991), Matrices and vector spaces, New York: M. Dekker, ISBN 978-0-8247-8419-5
10. Lang, Serge (1987), Linear algebra, Berlin, New York: Springer-Verlag, ISBN 978-0-387-96412-6
11. Lang, Serge (2002), Algebra, Graduate Texts in Mathematics, 211 (Revised third ed.), New York: Springer-Verlag, ISBN 978-0-387-95385-4, MR 1878556
12. Mac Lane, Saunders (1999), Algebra (3rd ed.), pp. 193–222, ISBN 978-0-8218-1646-2
13. Meyer, Carl D. (2000), Matrix Analysis and Applied Linear Algebra, SIAM, ISBN 978-0-89871-454-8
14. Roman, Steven (2005), Advanced Linear Algebra, Graduate Texts in Mathematics, 135 (2nd ed.), Berlin, New York: Springer-Verlag, ISBN 978-0-387-24766-3
15. Spindler, Karlheinz (1993), Abstract Algebra with Applications: Volume 1: Vector spaces and groups, CRC, ISBN 978-0-8247-9144-5
16. van der Waerden, Bartel Leendert (1993), Algebra (in German) (9th ed.), Berlin, New York: Springer-Verlag, ISBN 978-3-540-56799-8
17. Bourbaki, Nicolas (1987), Topological vector spaces, Elements of mathematics, Berlin, New York: Springer-Verlag, ISBN 978-3-540-13627-9
18. Bourbaki, Nicolas (2004), Integration I, Berlin, New York: Springer-Verlag, ISBN 978-3-540-41129-1
19. Braun, Martin (1993), Differential equations and their applications: an introduction to applied mathematics, Berlin, New York: Springer-Verlag, ISBN 978-0-387-97894-9
20. BSE-3 (2001) [1994], "Tangent plane", Encyclopedia of Mathematics, EMS Press
21. Choquet, Gustave (1966), Topology, Boston, MA: Academic Press
22. Dennery, Philippe; Krzywicki, Andre (1996), Mathematics for Physicists, Courier Dover Publications, ISBN 978-0-486-69193-0
23. Dudley, Richard M. (1989), Real analysis and probability, The Wadsworth & Brooks/Cole Mathematics Series, Pacific Grove, CA: Wadsworth & Brooks/Cole Advanced Books & Software, ISBN 978-0-534-10050-6
24. Dunham, William (2005), The Calculus Gallery, Princeton University Press, ISBN 978-0-691-09565-3

25. Evans, Lawrence C. (1998), Partial differential equations, Providence, R.I.: American Mathematical Society, ISBN 978-0-8218-0772-9
26. Folland, Gerald B. (1992), Fourier Analysis and Its Applications, Brooks-Cole, ISBN 978-0-534-17094-3
27. Gasquet, Claude; Witomski, Patrick (1999), Fourier Analysis and Applications: Filtering, Numerical Computation, Wavelets, Texts in Applied Mathematics, New York: Springer-Verlag, ISBN 978-0-387-98485-8
28. Ifeachor, Emmanuel C.; Jervis, Barrie W. (2001), Digital Signal Processing: A Practical Approach (2nd ed.), Harlow, Essex, England: Prentice-Hall (published 2002), ISBN 978-0-201-59619-9
29. Krantz, Steven G. (1999), A Panorama of Harmonic Analysis, Carus Mathematical Monographs, Washington, DC: Mathematical Association of America, ISBN 978-0-88385-031-2
30. Kreyszig, Erwin (1988), Advanced Engineering Mathematics (6th ed.), New York: John Wiley & Sons, ISBN 978-0-471-85824-9
31. Kreyszig, Erwin (1989), Introductory functional analysis with applications, Wiley Classics Library, New York: John Wiley & Sons, ISBN 978-0-471-50459-7, MR 0992618
32. Lang, Serge (1983), Real analysis, Addison-Wesley, ISBN 978-0-201-14179-5
33. Lang, Serge (1993), Real and functional analysis, Berlin, New York: Springer-Verlag, ISBN 978-0-387-94001-4
34. Loomis, Lynn H. (1953), An introduction to abstract harmonic analysis, Toronto-New York–London: D. Van Nostrand Company, Inc., pp. x+190, hdl:2027/uc1.b4250788
35. Narici, Lawrence; Beckenstein, Edward (2011). Topological Vector Spaces. Pure and applied mathematics (Second ed.). Boca Raton, FL: CRC Press. ISBN 978-1584888666. OCLC 144216834.
36. Schaefer, Helmut H.; Wolff, Manfred P. (1999). Topological Vector Spaces. GTM. 8 (Second ed.). New York, NY: Springer New York Imprint Springer. ISBN 978-1-4612-7155-0. OCLC 840278135.
37. Trèves, François (August 6, 2006) [1967]. Topological vector spaces, distributions and kernels. Mineola, N.Y.: Dover Publications. ISBN 978-0486453521. OCLC 853623322.
38. Historical references
39. Banach, Stefan (1922), "Sur les opérations dans les ensembles abstraits et leur application aux équations intégrales (On operations in abstract sets and their application to integral equations)" (PDF), Fundamenta Mathematicae (in French), 3: 133–181, doi:10.4064/fm-3-1-133-181, ISSN 0016-2736
40. Bolzano, Bernard (1804), Betrachtungen über einige Gegenstände der Elementargeometrie (Considerations of some aspects of elementary geometry) (in German)
41. Bourbaki, Nicolas (1969), Éléments d'histoire des mathématiques (Elements of history of mathematics) (in French), Paris: Hermann
42. Dorier, Jean-Luc (1995), "A general outline of the genesis of vector space theory", Historia Mathematica, 22 (3): 227–261, doi:10.1006/hmat.1995.1024, MR 1347828