Mem. S.A.It. Vol. 93, 17

Memorie della

The high-energy emission from the quiet Sun

Elena Orlando[1,2,3]

[1] University of Trieste and INFN, Trieste, via Valerio 2, I-34127 Trieste, Italy
[2] Hansen Experimental Physics Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA, e-mail: orlandele@gmail.com

Received: 26 december 2021; Accepted: 18 May 2022

Abstract. Galactic cosmic rays propagate in the heliosphere and interact with the solar surface and its surroundings. This generates non-thermal steady emission from the quiet Sun that may extend up to hundreds of GeV. The study of this emission provides a huge potential for understanding cosmic rays, the Sun and its environment, the solar activity, and the solar magnetic field. Here we review our recent results on the study of the quiet solar emission and we introduce forthcoming advancements.

Key words. The Sun – Cosmic Rays – Gamma rays

1. Introduction

The Sun is a gamma-ray source also in its quiescent state. Its steady emission is daily detected by the Fermi LAT telescope (Abdo et al., 2011; Barbiellini et al., 2014; Bartoli et al., 2019; Linden et al., 2018, 2020; Ng et al., 2016; Tang et al., 2018) and it was previously detected for the first time by Orlando & Strong (2008) in the EGRET data, who reported the detection of two components of the emission with a different spatial and spectral shape. These are the disk component produced by CR hadrons interacting with the solar surface (Seckel et al., 1991; Thompson et al., 1997; Mazziotta et al., 2020b; Li et al., 2020; Becker et al., 2020; Gutiérrez & Masip, 2020; Hudson et al., 2020; Niblaeus et al., 2019; Zhou et al., 2017) and the spatially extended Inverse-Compton (IC) component produced by CR electrons and positrons on the solar photons (Orlando & Strong, 2006; Moskalenko et al., 2006; Orlando & Strong, 2021). The latter, which extends in the entire heliosphere, is brighter for directions close to the Sun, but it has a broad distribution, effectively covering the whole sky. The flux of both gamma-ray components is expected to change over the solar cycle due to the modulation of the CRs in the heliosphere, and it is expected to be anti-correlated with the solar activity. The two emission components have been more clearly disentangled in the Fermi LAT data (Abdo et al., 2011). However, present model are not able to totally describe the observed emission (Abdo et al., 2011) and some unexpected features showed up in the data (e.g. Tang et al., 2018).

2. The quiet Sun at high energies

This sections discusses recent results from the theoretical and observational point of view.

2.1. Model advancements

Orlando & Strong (2006) and Moskalenko et al. (2006) independently theorized the existence of an extended IC emission from scattering by CR electrons on solar photons. Because the IC emission depends on the electron density and spectrum, and the electrons depend on the solar activity and on the position in the heliopshere, in our very recent work (Orlando & Strong, 2021) we obtained updated IC models that account for various formulation of the solar modulation and activity. In particular, our IC models incorporate the local interstellar all-electron spectra that fit Pamela (Adriani et al., 2009) and AMS-02 (Aguilar et al., 2014) measurements at 1 AU. In more detail, we defined two baseline all-electron models: the first one mainly based on the Pamela all-electron spectrum for the period of 2008, which we consider the representative model for periods of solar minimum; the second one mainly based on the AMS-02 all-electron spectrum for the period of 2013, which we consider the representative model for periods of solar maximum. Both modeled spectra are fitted to AMS-02 data above 40 GeV, where AMS-02 data are more precise than Pamela and the solar modulation is not important. Figure 1 shows the resulting IC spectral intensity for various angular distances from the Sun based on the AMS02 and Pamela all-electron spectra compared with observations.

Our modeling provides the basis for analyzing and interpreting high-energy data of the Sun. Recently, we have started working on modeling the CR propagation of electrons accounting for diffusion processes in the heliosphere and solar magnetic field (Petrosian et al., 2022). IC models will be updated in agreement (Orlando et al., 2022a).

2.1.1. Extensions at MeV and TeV energies

Model predictions of the IC emission that implement recent CR measurements show (Orlando & Strong, 2021) that this component is important also at MeV energies, as illustrated in Figure 1. With the MeV proposed telescopes' sensitivity (e.g. Moiseev, 2019; McEnery et al., 2019; de Angelis et al., 2018) the spectrum of the CR electrons as a function of the position in the heliosphere can then be tested against gamma-ray data at MeV energies where the solar modulation effect is maximum and the various models can be more easily differentiated. Hence, MeV data will allow to access the low-energy part of the electron spectrum in close proximity of the Sun and in the inner helisphere, and it will also enable studies of CR propagation in the inner heliosphere. As for the Fermi LAT (Johannesson & Orlando, 2013), given the broad distribution of the IC emission on the sky, we showed (Orlando & Strong, 2021) that the solar contribution to the diffuse MeV background should be accounted for when analyzing gamma-ray data. Investigating possible TeV emission from

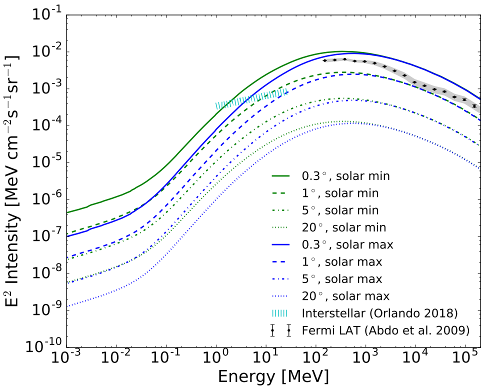

Fig. 1. Resulting IC spectral intensity for various angular distances from the Sun based on the AMS02 and Pamela all-electron spectra. Solid lines are the spectral intensity at 0.3° from the Sun, while dashed lines at 1° from the Sun, dotted-dashed lines at 5° from the Sun, and dotted lines at 20° from the Sun. Blue lines represent the solar maximum condition (all-electron model that fits AMS-02 data), while the green lines represents the solar minimum condition (all-electron model that fits Pamela data). Black points and grey region are data and systematic errors of the total emission at intermediate latitudes by Fermi-LAT (Abdo et al., 2009), in agreement with our recent work (Mizuno et al., 2022). The cyan region shows the interstellar emission at intermediate latitudes as predicted in Orlando (2018). Figure adapted from Orlando & Strong (2021).

the quiet Sun has recently sparked interest, especially because of the HAWC (Albert et al., 2018) and ARGO (Bartoli et al., 2019) experiments that obtained upper limits to the emission from the solar disk, LHAASO (Bai et al., 2019) and the forthcoming next generation SWGO (Albert et al., 2019). Hence, in Orlando & Strong (2021) we extended our calculations of the IC emission to the TeV energy band.

2.2. Gamma-ray observations Interesting features in the solar emission

The first evidence of the gamma-ray emission from the quietscent Sun was found by Orlando & Strong (2008) analyzing the entire archivial EGRET data. The spectrum and the distribution of the IC component was found to be in agreement with model predictions (Moskalenko et al., 2006; Orlando & Strong, 2006), while the flux of the disk component was closer to the "naive" model of Seckel et al. (1991) and exceeding the "nominal" one. The results of the analysis of observations of the solar emission during the first 18 months of the Fermi LAT mission were reported in Abdo et al. (2011). A recent analysis of 6 years of Fermi-LAT observations (Ng et al., 2016) reported variations of the flux of the disk (maybe total) component that anti-correlated with the solar activity. However, the IC component that is more difficult to analyze was not the subject of that study. Even more recent works (Tang et al., 2018; Linden et al., 2018) updated the analysis for almost the entire 11-year cycle and observed some unexpected features. Dedicated works from our team are in progress (Fermi LAT Collab., 2022). This work includes also the IC component, which can not be neglected. We are also working in localizing high-energy photons from the solar disk (Arsioli et al., 2022).

2.3. Detection of luminous stars in gamma rays

Besides the Sun, no other disk or halo from single stars has ever been detected in gamma rays. However, by assuming a cosmic ray spectrum similar to that observed on Earth such as in our recent works (Orlando, 2018; Mizuno et al., 2022), we estimated the predicted gamma-ray emission of the most luminous nearby stars to be high enough to be detected by the Fermi LAT after its first decade of operations (Orlando & Strong, 2006, 2021). Hence, very recently (de Menezes et al., 2021) we used 12 years of Fermi-LAT observations along with our IC models (Orlando & Strong, 2006, 2021) to study the most luminous nearby stars, both individually and via stacking analysis. Our results (de Menezes et al., 2021) showed no significant gamma-ray emission, but allowed us to obtain upper limits for an average local density of electrons in the surroundings of our targets to be less than twice of that observed for the Solar system.

2.4. A new component of the quiet Sun

In an ongoing work (Orlando et al., 2022b) we estimate a new component: the synchrotron emission produced by Galactic cosmic rays on the magnetic field of the Sun and of the heliosphere. To the best of our knowledge, this is the first time that such an emission component has been considered when exploring the quiet Sun. The expected spatial distribution of this emission, which we found to be maximum in the close vicinity of the Sun. This new emission component provides a more complete description of the quiet Sun and opens a new window for understanding not only cosmic rays in the Heliosphere and close to the Sun, but also the Sun itself, its environment, and the solar magnetic field.

3. Conclusions

The Sun is a source of high-energy emission in its quietscient state. In this paper, we have reviewed our most recent results related to the study of this emission, including model advancements. We have also presented preliminary results of our currently ongoing analyses.

Acknowledgements. E.O. acknowledge support from the Accordo Attuativo ASI-INAF n. 2017-14-H.0.

References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, Physical Review Letters, 103, 251101

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2011, ApJ, 734, 116

Adriani, O., Barbarino, G. C., Bazilevskaya, G. A., et al. 2009, Nature, 458, 607

Aguilar, M., Aisa, D., Alvino, A., et al. 2014, Physical Review Letters, 113, 121102

Albert, A., Alfaro, R., Ashkar, H., et al. 2019, arXiv:1902.08429

Albert, A., Alfaro, R., Alvarez, C., et al. 2018, Phys. Rev. D, 98, 123011.

Arsioli, Orlando, Raino', Giglietto in preparation

Bai, X., Bi, B. Y., Bi, X. J., et al. 2019, arXiv:1905.02773

Barbiellini, G., Bastieri, D., Bechtol, K., et al. 2014, ApJ, 784, 118.

Bartoli, B., Bernardini, P., Bi, X. J., et al. 2019, ApJ, 872, 143.

Becker Tjus, J., Desiati, P., Döpper, N., et al. 2020, A&A, 633, A83.

de Angelis, A., Tatischeff, V., Grenier, I. A., et al. 2018, Journal of High Energy Astrophysics, 19, 1. doi:10.1016/j.jheap.2018.07.001

de Menezes, R., Orlando, E., Di Mauro, M., et al. 2021, MNRAS, 507, 680.

Fermi LAT Collaboration in preparation

Gutiérrez, M. & Masip, M. 2020, Astroparticle Physics, 119, 102440.

Hudson, H. S., MacKinnon, A., Szydlarski, M., et al. 2020, MNRAS, 491, 4852.

Hudson, H. S., 1989, Proc Gamma Ray Observatory Workshop (Greenbelt: Goddard Space Flight Center), 4-351

Johannesson, G. & Orlando, E. 2013, International Cosmic Ray Conference, 33, 3106

Li, Z., Ng, K. C. Y., Chen, S., et al. 2020, arXiv:2009.03888

Linden, T., Zhou, B., Beacom, J. F., et al. 2018, Phys. Rev. Lett., 121, 131103. doi:10.1103/PhysRevLett.121.131103

Linden, T., Beacom, J. F., Peter, A. H. G., et al. 2020, arXiv:2012.04654

Mazziotta, M. N., Loparco, F., Serini, D., et al. 2020, Phys. Rev. D, 102, 022003.

Mazziotta, M. N., Luque, P. D. L. T., Di Venere, L., et al. 2020, Phys. Rev. D, 101, 083011.

McEnery, J., van der Horst, A., Dominguez, A., et al. 2019, BAAS

Mizuno, T.; Hayashi, K.; Metzger, J.; Moskalenko, I.; Orlando, E. et al, ApJ submitted

Moiseev, A. 2019, 36th International Cosmic Ray Conference (ICRC2019), 36, 585

Moskalenko, I. V., Porter, T. A., & Digel, S. W. 2006, ApJL, 652, L65

Ng, K. C. Y., Beacom, J. F., Peter, A. H. G., et al. 2016, Phys. Rev. D, 94, 023004. doi:10.1103/PhysRevD.94.023004

Niblaeus, C., Beniwal, A., & Edsjö, J. 2019, JCAP, 2019, 011.

Orlando, E. & Strong, A. W. 2007, Ap&SS, 309, 359.

Orlando, E., & Strong, A. W. 2008, A&A, 480, 847

Orlando, E. 2018, MNRAS, 475, 2724. doi:10.1093/mnras/stx3280

Orlando, E. & Strong, A. 2021, JCAP, 2021, 004.

Orlando, E., Strong, A., & Petrosian, V., in preparation

Orlando, E., Petrosian, V., & Strong, A., in preparation

Petrosian, V., Orlando, E., & Strong, A., in preparation

Seckel, D., Stanev, T., & Gaisser, T. K. 1991, ApJ, 382, 652

Tang, Q.-W., Ng, K. C. Y., Linden, T., et al. 2018, Phys. Rev. D, 98, 063019.

Thompson, D. J., Bertsch, D. L., Morris, D. J., & Mukherjee, R. 1997, J. Geophys. Res., 102, 14735

Zhou, B., Ng, K. C. Y., Beacom, J. F., et al. 2017, Phys. Rev. D, 96, 023015.