Istituto Ricerche Solari Locarno

Rapporto 2020

Rapporto alla Fondazione Istituto Ricerche Solari Locarno sulla situazione dell'Istituto alla fine del 2020 e sul piano di lavoro per il 2021

Relatori:	Dr. Michele Bianda Staff dell'IRSOL	
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Proprietario:	Fondazione Istituto Ricerche Solari Locarno Membri: Cantone Ticino, Comune di Locarno, AIRSOL *)	
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Prof. Dr. Marzio Nessi	CERN, Ginevra
Prof. Dr. Manfred Schüssler	MPS, Göttingen, Germania

Locarno-Monti, 31 maggio 2021

*) *AIRSOL, Associazione Istituto Ricerche Solari Locarno*

Indice

1 PREMESSA

L'attività di ricerca scientifica dell'Istituto Ricerche Solari Locarno (IRSOL) è incentrata nel campo della spettropolarimetria solare.

Un importante evento avvenuto in febbraio è consistito nella votazione positiva del Gran Consiglio ticinese sul messaggio a favore della affiliazione del IRSOL all'USI, diventata effettiva il 1 gennaio 2021.

Nel 2020 gli effetti della situazione pandemica originata dal virus SARS-CoV-2 hanno avuto un grande effetto sull'organizzazione del lavoro dell'istituto. Si è fatto largo uso del lavoro da casa cercando di ottimizzare la possibilità offerte dalla connessione in rete per lo scambio di dati e per l'interazione tramite videoconferenze. All'IRSOL ci si è concentrati su lavori tecnici e la registrazione di dati osservativi. Nel bilancio della situazione, considerando comunque la drammaticità del periodo, possono essere individuati elementi positivi. Il lavoro svolto in queste condizioni finora inusuali ha comunque permesso di raggiungere diversi risultati come descritto nel presente rapporto. Non è stato necessario ricorrere ad interruzioni del lavoro o alla richiesta di aiuti finanziari d'emergenza. Quanto è sicuramente mancato è stata la possibilità di interagire di persona, nel corso di visite di lavoro o di congressi, con colleghi.

Il lavoro scientifico ha permesso di pubblicare 13 articoli con personale dell'IRSOL come autori su riviste referenziate e 13 articoli su atti di conferenze. Da evidenziare che la tesi di dottorato di Gioele Janett è stata premiata con l'Edith Alice Müller Award 2020. Inoltre il team di CLASP2, di cui fanno parte Luca Belluzzi e Ernest Alsina Ballester, è stato premiato con il NASA's Group Achievement Honor Award.

Un sistema ZIMPOL è stato fornito al Politecnico di Zurigo per ricerche nel campo della biologia e farmaceutica.

Oltre ai lavori scientifici vanno menzionati i lavori del consiglio di fondazione per coordinare con l'ufficio del controllo delle fondazioni a Berna l'accordo di affiliazione ed il nuovo statuto della FIRSOL.

Con la SUPSI abbiamo comniciato a valutare vari scenari per la manutenzione e lo sviluppo del sistema ZIMPOL.

La ristrutturazione dell'istituto è continuata: sono stati coordinati i lavori per collegarsi alla rete regionale dell'USI tramite fibra ottica, adattare il cablaggio di rete dell'osservatorio, preparare un nuovo allacciamento alla linea elettrica, allacciarci alla canalizzazione di Orselina e riasfaltare la strada di accesso.

2 PERSONALE

Organizzazione generale
L'organizzazione generale è diretta dal presidente della FIRSOL, Prof. Dr. Philippe Jetzer (Istituto di fisica dell'Università di Zurigo).

Direttorato
La direzione dell'IRSOL è affidata ad un direttorio composto da:

Prof. Dr. Svetlana Berdyugina (direttrice del Leibniz-Institut für Sonnenphysik, KIS)

Dr. Michele Bianda

Prof. Dr. Jan Olof Stenflo

La vice-direzione è affidata al Dr. Renzo Ramelli

Staff scientifico: personale fisso e postdoc

Dr. Ernest Alsina Ballester (dal 1 febbraio 2018) *

Dr. Luca Belluzzi (pure affiliato al KIS)

Dr. Michele Bianda

Dr. Daniel Gisler

Dr. Nuno Guereiro (dal 1 maggio 2019) ***

Dr. Gioele Janett (dal 1 luglio 2019, part time) ***

Ing. ETHZ Boris Liver

Dr. Fabio Riva (dal 1 aprile 2020) **

Dr. Oskar Steiner (part time con il KIS)

Dr. Franziska Zeuner (dal 1 dicembre 2019) ****

Prof. Dr. Jan Olof Stenflo, emeritus ETHZ, affiliato all'IRSOL

Ing. Christian Monstein, precedentemente all'ETHZ, affiliato all'IRSOL

* Finanziato tramite il progetto del Fondo Nazionale, 200021_175997
** Finanziato tramite il progetto del Fondo Nazionale, 200020_182094
*** Finanziato tramite il progetto del Fondo Nazionale, CRSII5_180238
**** Finanziata tramite il progetto H2020 SOLARNET

Staff amministrativo e tecnico

Katya Gobbi (segretaria)

Gianpaolo Mari

Dottorandi

MSc. José Roberto Canivete Cuissa (dal 1 settembre 2019) *

MSc. Emilia Capozzi (dal 1 aprile 2017) **

MSc. Simone Riva (dal 1 ottobre 2018) ***

Questi progetti di dottorato sono finanziati dal Fondo Nazionale.
* Direttore di tesi: Prof. Dr. Romain Teyssier dell'Università di Zurigo
** Direttore di tesi: Prof. Dr. Georges Meynet dell'Università di Ginevra
*** Direttore di tesi: Prof. Dr. Rolf Krause, USI, Lugano

Masterandi

Andrea Battaglia, dal 1 gennaio al 17 aprile. Lavoro di master seguito dalla Prof. Dr. Louise Harra, PMOD-WRC e ETHZ, e dal Dr. Oskar Steiner

Collaborazione con il Leibniz-Institut für Sonnenphysik, KIS

Regolato da un contratto con il KIS, il Dr. Daniel Gisler lavora a tempo parziale a Freiburg sul progetto Visible Tunable Filter (VTF) per il telescopio solare statunitense DKIST.

Stages scientifici, lavori a tempo determinato

Martina Mongillo (dal 27 luglio al 14 agosto): stage nell'ambito del programma Estage

Civilisti

Nel corso del 2020 hanno lavorato all'IRSOL:

Ezio Bonetti (dal 2 marzo al 1 maggio)

Andrea Battaglia (dal 20 aprile al 9 luglio)

Christian Skorski (dal 22 giugno al 28 agosto)

Kilian Taddei (dal 6 luglio al 31 luglio)

RINGRAZIAMENTI

- **Ing. Boris Liver** Con il 2020 termina la collaborazione con il nostro responsabile del sistema informatico e del sistema ZIMPOL, Ing. Boris Liver. Grazie al suo impegno è stato possibile avere a disposizione un sistema informatico funzionante da decenni nonostante la connessione basata su un collegamento in rame, installato dalle PTT negli anni 50, e con un budget limitato. Ha pure garantito la continuità del sistema ZIMPOL dal 2015. Lo ringraziamo per la collaborazione.

OBITUARIO

- **Prof. Dr. Gerd Küveler, 3.01.1950 - 14.09.2020†**

  È venuto a mancare, doppo una lunga lotta contro una subdola malattia, Gerd Küveler. Per molti anni ha contribuito in modo sostanziale allo sviluppo dell'IRSOL. Dottorando alla Universitäts Sternwarte di Göttingen aveva svolto le misure per la sua tesi all'IRSOL, quando questi apparteneva all'università di Göttingen, e questo all'inizio degli anni '80. Diventato professore alla Fachhochschule di Wiesbaden, a partire dal 1990 ha iniziato una collaborazione con l'IRSOL che ha portato alla realizzazione di un centinaio di lavori di diploma, bachelor o master aventi come tema lo sviluppo di strumenti per l'IRSOL. Ancora adesso stiamo utilizzando strumenti sviluppati grazie a questa collaborazione. La sua serietà professionale, il suo buonumore, la sua fine ironia sono legate alla vita dell'istituto degli ultimi decenni. Lo avevamo come ospite per un paio di volte all'anno a Locarno; progettare nuovi e complessi strumenti o pensare a migliorie di quelli esistenti erano momenti in cui si alternavano sedute lavorative molto impegnate a momenti di simpatica conviavilità.

- **Anneliese Alge, 1.08.1934 - 13.09.2020†**

  Fino a pochi anni fa, nei rapporti di lavoro veniva riportato il contributo che Anneliese portava all'IRSOL. Moglie di Edy, collaboratore tecnico dell'IRSOL a partire dai primi passi dell'istituto sotto la gerenza della FIRSOL venuto a mancare nel 2001, Anneliese fino al 2017 aveva abitato all'IRSOL aiutando nella manutenzione dell'istituto e prendendosi cura delle necessità degli ospiti. Di lei rimarrà caro il ricordo della sua gentilezza e disponibilità ad aiutare il prossimo.

3 SCIENTIFIC WORK

The overall goal of the scientific activity carried out at IRSOL is to gain a better physical understanding of the magnetic fields present in the solar atmosphere. Solar magnetic fields can be investigated by analyzing the signatures that they leave, through different physical mechanisms, on the spectral and polarization properties of the electromagnetic radiation. In general, the development and application of a given diagnostic method requires:

a) modeling the generation and transfer of polarized radiation in the solar atmosphere, taking the above-mentioned mechanisms into account, in order to identify specific polarization signals encoding information on the magnetic fields;

b) developing instruments capable of observing such signals, and performing precise observations;

c) comparing the observed signals with the results of theoretical calculations performed with realistic simulations of the solar atmosphere.

The research work at IRSOL builds on three pillars: observations and instrument development, theoretical modeling, and numerical simulation, yet they are all focused on the unique topic of polarimetry of the solar atmosphere.
A detailed description of all the scientific works that are presently carried out at IRSOL, together with the result obtained in the past year, is provided below.

3.1 Theoretical and numerical modeling of polarization signals

3.1.1 Modeling the enigmatic scattering polarization signal of the Na I D_1 line

The investigation of the enigmatic scattering polarization signal of the Na I D_1 line, which was started in 2018 within the framework of the SNSF project "The magnetic sensitivity of strong chromospheric lines: from the CLASP experiments to the Na I D_1 paradox" (project no. 200021_175997), was successfully completed in 2020. We recall that this project allowed opening a three-year post-doc position (01.02.2018 – 31.01.2021), which was offered to Dr. Ernest Alsina Ballester. The first part of the project was dedicated to the development of a new numerical code capable of solving the radiative transfer (RT) problem for polarized radiation, in one-dimensional (1D) models of the solar atmosphere, for the case of a two-term atom with hyperfine structure (HFS), in non-local thermodynamic equilibrium (NLTE) conditions. The code accounts for scattering polarization and partial frequency redistribution (PRD) effects, due to both elastic collisions and the Doppler effect, and allows including the impact of magnetic fields of arbitrary strength and orientation. By applying this code, we could reproduce remarkably well some recent observations of the scattering polarization signal of the Na I D_1 line, finding that the best fit is obtained when a magnetic field of about 15 G is included in the modeling. This result provides a very convincing solution to the solar Na I D_1 paradox, which has challenged solar physicists for more than 20 years. In addition, our calculations allowed us to investigate the magnetic sensitivity of the scattering polarization signal across the D_1 and D_2 lines due to the combined action of the Hanle, Zeeman, and MO effects, thus opening a new window for exploring the elusive magnetic fields present in the lower chromosphere. A letter highlighting the main results of this work was submitted to the journal *Physical Review Letters* [1], and a more detailed paper is presently in preparation [2].

Related research work and follow-up investigations
In addition to enabling the modeling of the scattering polarization signal of the sodium D-lines, the aforementioned RT code allowed us to identify suitable approximations for modeling the scattering polarization wings of strong resonance lines. These approximations allow a substantial simplification of the calculations, and are of particular interest for the SNSF Sinergia project CRSII5_180238, which is presently ongoing at IRSOL (see Sect. 3.1.4). A paper that describes the code in detail, presents such approximations, and discusses their suitability is presently in preparation [3]. The same code also allowed us to perform a detailed investigation on the polarization signals of the K I D-lines, for which a two-term atom with HFS has to be considered. Such an investigation is of current interest because these lines will soon be observed as part of the SUNRISE-3 experiment. A paper on this work is presently in preparation [4]. Finally, in cooperation with Dr. A. Paganini from the University of Leicester (UK), we developed a fast and accurate new method for calculating the angle-averaged redistribution matrix. This method is particularly useful when considering complex atomic models. This work, submitted to the journal Astronomy & Astrophysics in 2020, has been recently published [5].

Researchers involved:
IRSOL: E. Alsina Ballester, L. Belluzzi
External: J. Trujillo Bueno (IAC, Spain), A. Paganini (Univ. of Leicester, UK)

Publications:
[1] Alsina Ballester, E., Belluzzi, L., & Trujillo Bueno, J. *A long-standing solar paradox solved*, Phys. Rev. Lett. [submitted]
[2] Alsina Ballester, E., Belluzzi, L., & Trujillo Bueno, J. *The physical origin and the diagnostic potential of the scattering polarization signals of the Na* I *doublet* [in prep.]
[3] Alsina Ballester, E., Belluzzi, L., & Trujillo Bueno, J. *Modeling scattering polarization with PRD in two-term atomic models: numerical methods and useful approximations* [in prep.]
[4] Alsina Ballester, E., Belluzzi, L., & Trujillo Bueno, J. *The polarization of the K* I *D-lines: physical origin and magnetic sensitivity* [in prep.]
[5] Paganini, A., Hashemi, B., Alsina Ballester, E., & Belluzzi, L. 2021, *Fast and accurate approximation of the angle-averaged redistribution function for polarized radiation*, A&A, 645, A4

3.1.2 The CLASP experiments

The SNSF project "The magnetic sensitivity of strong chromospheric lines: from the CLASP experiments to the NaI D1 paradox" also supported the participation of IRSOL in the international CLASP1 (Chromospheric Ly-alpha SpectroPolarimeter) and CLASP2 (Chromospheric Layer SpectroPolarimeter) sounding rocket experiments. We recall that these experiments provided unprecedented spectropolarimetric observations of the H I Ly-α line and of the Mg II h and k lines, respectively. In this context, our activity has been mainly focused on the investigation of the magnetic sensitivity of the scattering polarization wings of the H I Ly-α line via MO effects, and to the interpretation of the CLASP data on the basis of this mechanism. During 2020, we focused our attention on the modeling of the frequency-integrated scattering polarization signals observed across the Ly-α line, in order to replicate the observations of the slit-jaw system of CLASP1. Remarkably, the slit-jaw system was able to obtain two-dimensional (2D) borad-band images not only in intensity but also in Stokes Q/I, representing a measurement of linear polarization. Our investigation revealed that such broad-band linear polarization signals are dominated by the contribution from the line wings, and are thus strongly sensitive to MO effects. Indeed, by making reasonable assumptions on the large-scale distribution of magnetic fields in the chromosphere, the 2D images captured by the slit-jaw system could be satisfactorily reproduced. The results of this work are being collected in a paper [1]. Interestingly also the slit-jaw system of CLASP2 collected broad-band images across the H I Ly-α line, in Stokes I, Q, and U. A follow-up work based on this data will be carried out as soon as such data will be reduced and shared by our Japanese colleagues. During 2020, part of the CLASP2 spectropolarimetric data have been analyzed and exploited by the CLASP2 team to obtain a map of the magnetic field from the photosphere to the base of the corona. This study was submitted to *Science Advances* in 2020, and it was published at the beginning of 2021 [2], receiving attention and appreciation by the community. In 2020, NASA granted the CLASP2 team the *Group Achievement Honor Award*. A third experiment, CLASP2.1, was proposed in 2020, and it was recently approved by NASA (launch scheduled in 2022).

Researchers involved:
IRSOL: E. Alsina Ballester, L. Belluzzi
External: the CLASP team (USA, Japan, Europe)

Publications:
[1] Alsina Ballester, E., Belluzzi, L., & Trujillo Bueno, J., *Signatures of magneto-optical effects in the CLASP broadband linear polarization signals* [in prep.]
[2] Ishikawa, R., Trujillo Bueno, J., del Pino Aleman, T. et al. (25 co-authors, the CLASP team) 2021, *Mapping Solar Magnetic Fields from the Photosphere to the Base of the Corona*, Sci. Adv., 7, 8

3.1.3 The magnetic sensitivity of the scattering polarization wings of Ca I 4227

Another objective of the aforementioned SNSF project was to find observational proof of the theoretically predicted sensitivity to MO effects of the scattering polarization wings of the Ca I 4227 Å line and to explore its potential for magnetic field diagnostics. This study, which combined observations with the IRSOL instrumentation and theoretical modeling, was proposed as part of the PhD thesis of MSc. E. Capozzi. The first part of such work was observational in nature. Making use of spectropolarimetric observations taken with ZIMPOL at both IRSOL and GREGOR, it was possible to acquire compelling evidence for the operation of such effects. Indeed, these observations revealed a clear correlation between photospheric longitudinal magnetic fields (leaving their signatures in the circular polarization signals of nearby iron lines) and the rotation of the plane of linear polarization of the Ca I 4227 Å line wings, characteristic of the impact of MO effects. This work was completed in 2020 and published in the journal Astronomy & Astrophysics [1]. As the next step, MSc. Capozzi carried out a theoretical investigation on such signals through RT calculations focused on the impact of MO effects. A particularly interesting discovery of this investigation was that, although both the Zeeman and MO effects arise from the longitudinal component of the magnetic field, the former is sensitive only to the magnetic flux, whereas the latter depends also on the fraction of the resolution element occupied by the magnetic field (or its filling factor). The main results of this work were recently submitted to Astronomy & Astrophysics [2]. A second article, exposing this investigation in more details is currently in preparation [3].

Researchers involved (observational work):
IRSOL: E. Capozzi, E. Alsina Ballester, L. Belluzzi, M. Bianda, R. Ramelli, S. K. Dahara

Researchers involved (theoretical work):
IRSOL: E. Capozzi, E. Alsina Ballester, L. Belluzzi
External: J. Trujillo Bueno (IAC, Spain)

Publications:
[1] Capozzi, E., Alsina Ballester, E., Belluzzi, L., Bianda, M., Dahara, S. K., & Ramelli, R. 2020, *Observational indications of magneto-optical effects in the scattering polarization wings of the Ca* I *4227 Å line*, A&A, 641, A63
[2] Capozzi, E., Alsina Ballester, E., Belluzzi, L., & Trujillo Bueno, J., *The polarization angle in the wings of Ca* I *4227: a new observable for diagnosing unresolved photospheric magnetic fields*, A&A [submitted]
[3] Capozzi, E., Alsina Ballester, E., Belluzzi, L., & Trujillo Bueno, J., *The magnetic sensitivity and diagnostic potential of Ca* I *4227 scattering polarization wings* [in prep.]

3.1.4 3D modeling of scattering polarization with angle-dependent PRD effects

The research activity on the modeling of scattering polarization in three-dimensional (3D) models of the solar atmosphere, accounting for angle-dependent (AD) partial frequency redistribution (PRD) effects (SNSF Sinergia project no. CRSII5_180238), continued during the whole 2020, with focus on different topics and investigations. On June 1st 2020, Dr. P. Benedusi joined the project, filling the post-doc position in the group of the project partner Prof. R. Krause at the Institute of Computational Sciences (ICS).

In 2020, a MATLAB code for solving the RT problem for polarized radiation on multicore architectures was completed and debugged. In particular, this code can consider 1D realistic models of the solar atmosphere for the case of a two-level atom with unpolarized and infinitely-sharp lower level, in NLTE conditions, taking AD PRD effects into account. This code is presently applied to explore and test new methods and approaches that could be particularly suitable (e.g., in terms of memory requirements or computing time) in view of the transition to the more general 3D case. Moreover, it has been used to perform a detailed comparison between the results of PRD calculations carried out in the general AD case and under the angle-averaged (AA) simplifying assumption. This investigation was focused on the Ca I 4227 Å line, including magnetic fields of arbitrary intensity and orientation. A paper explaining the approach to the problem and showing the results of this comparison is presently in preparation [1]. The same code also allows including the impact of bulk velocities (both vertical and non-vertical). Performing calculations in the presence of velocities will be the next goal of this working package. First steps in this direction have already been carried out during 2020 thanks to the work of Dr. N. Guerreiro, who also continued the development and debugging of a similar numerical code, written in FORTRAN. This second code will have the advantage of allowing parallel calculations using multiple nodes of the cluster of ICS.

In parallel, MSc. S. Riva continued his PhD work, focused on the development and optimization of methods and algorithms for performing specific steps of the above-mentioned problem (e.g., the calculation of the redistribution matrix and the evaluation of the scattering integral) with the main aim of reducing the computing time and fully exploiting the computing power of present day computers. Furthermore, Dr. G. Janett and Dr. P. Benedusi started an in-depth investigation of different iterative methods for the solution of the NLTE RT problem for polarized radiation. This work, which is based on a linear benchmark RT problem, formulated in the limit of complete frequency redistribution (CRD), led to a series of two papers, which have been recently submitted to Astronomy & Astrophysics. The first one is focused on the stationary iterative methods that are commonly applied in the field of RT. The paper provides a detailed analysis of their stability and convergence properties, in combination with different formal solvers [2]. The second paper is instead focused on Krylov methods, which are gradually replacing stationary iterative methods in many research fields [3]. The work explores the properties and potentialities of these methods in the field of the transfer of polarized radiation, following the pioneering works carried out by the group of Prof. Nagendra at the Indian Institute of Astrophyiscs (IAA, Bangalore, India). In the light of the very interesting results of this latter work, Krylov methods will also be used to solve the considered RT problem for polarized radiation, accounting for AD PRD effects. As a first preliminary study, a Krylov method has already been implemented in the aforementioned MATLAB code.

Researchers involved:
IRSOL: L. Belluzzi, N. Guerreiro, G. Janett, S. Riva, E. Alsina Ballester
Sinergia partners: R. Krause (ICS, Lugano), P. Benedusi (ICS, Lugano), J. Trujillo Bueno (IAC, Spain), A. Shukhorukov (IAC, Spain), J. vStěpán (ASCR, Czech Republic)

Publications:
[1] Janett, G., Alsina Ballester, E., Guerreiro, N., Riva, S., del Pino Alemán, T., Trujillo Bueno, J., & Belluzzi, L., *Modeling of scattering polarization in Ca* I *4227 with angle-dependent partial frequency redistribution* [in prep.]
[2] Janett, G., Benedusi, P., Belluzzi, L., & Krause, R., *Numerical solutions to linear transfer problems of polarized radiation - I. Algebraic formulation and stationary iterative methods* [submitted]
[3] Benedusi, P., Janett, G., Belluzzi, L., & Krause, R., *Numerical solutions to linear transfer problems of polarized radiation - II. Krylov methods and matrix-free implementation* [submitted]

3.2 Magnetohydrodynamic Simulations of the Solar and Stellar Atmospheres

3.2.1 A dynamical equation for the swirling strength

We studied the dynamics of vortical motions in the solar atmosphere by employing and deriving the evolution equation of a quantity called swirling strength, which can be considered a generalization of the vorticity. The vorticity and its equation were typically used for the characterization and dynamical studies of vortices in the past. However, the vorticity can be biased by the presence of shear flows, while the swirling strength offers a more precise alternative but its evolution equation was not known so far. Therefore, we successfully explored the possibility of deriving a dynamical equation for the swirling strength and applied it to analyze radiative magneto-hydrodynamical simulations of the solar atmosphere produced with the CO5BOLD code. This equation constitutes a novel tool that is suitable for the analysis of a wide range of problems in (magneto-)hydrodynamics. By applying this equation to numerical models, we found that hydrodynamical and magnetic baroclinicities are the driving physical processes responsible for the vortex generation in the convection zone and photosphere. Higher up in the chromosphere, the magnetic terms alone dominate. Presently, we are preparing a comprehensive review on vortex motions in the solar atmosphere in collaboration with a team of researchers at the International Space Science Institute (ISSI) under the leadership of K. Tziotziou and E. Scullion.

Researchers involved:

IRSOL: J.R. Canivete Cuissa, O. Steiner
External: K. Tziotziou (Nat. Obs. of Athens), E. Scullion (Northumbria Univ., Newcastle upon Tyne)

Publications:

J.R. Canivete Cuissa & O. Steiner 2020, A&A 639, A118

K. Tziotziou with J.R. Canivete Cuissa, O. Steiner et al. in prep.

3.2.2 The Alfvénic nature of chromospheric swirls

We analyzed results from numerical simulations of the solar atmosphere carried out at IRSOL with the Piz Daint supercomputer of the Centro Svizzero di Calcolo Scientifico (CSCS), focusing on vortical motions and their dynamics. For the analysis, we made use of the swirling strength and its dynamical equation, which we previously derived from the fundamental equations of magnetohydrodynamics.

We found that swirls propagate upward with the local Alfvén speed as unidirectional pulses driven by magnetic tension forces alone. In the photosphere and low chromosphere, the rotation of the plasma co-occurs with a twist in the upwardly directed magnetic field that is in the opposite direction of the plasma flow. All together, these are clear characteristics of torsional Alfvén waves. Yet, the Alfvén wave is not oscillatory but takes the form of a unidirectional pulse. New is that these Alfvén pulses naturally and self-consistently emerge from realistic numerical simulations of the solar atmosphere and must not be artificially excited. At the base of the chromosphere, we find a mean net upwardly directed Poynting flux of $12.8 \pm 6.5\,\mathrm{kW\,m^{-2}}$, which is mainly due to swirling motions. For a comparison, the energy flux needed to compensate the radiative losses in the chromosphere is $4.3\,\mathrm{kW\,m^{-2}}$.

Researchers involved:

IRSOL: A. Battaglia, J.R. Canivete Cuissa, O. Steiner
External: A.A. Bossart (EPFL, Lausanne), F. Calvo (Univ. Stockholm), L. Harra (ETH-Zürich and PMOD, Davos)

Publications:

A.F. Battaglia, J.R. Canivete Cuissa, F. Calvo, A.A. Bossart, & O. Steiner 2021, A&A 649, A121
A.F. Battaglia, Master Thesis, ETH-Zürich (2020)

3.2.3 Interaction of Magnetic Fields with a Vortex Tube at Solar Subgranular Scale

We analyzed snapshots of a magnetohydrodynamic numerical simulation of the solar atmosphere, previously carried out at IRSOL by F. Calvo on the Piz Daint supercomputer at CSCS. We found that horizontal vortex tubes that form at the edges of granules redistribute and transport magnetic field to the solar surface, causing a polarimetric signature very similar to what is observed. We thus witness a mechanism capable of transporting magnetic flux to the solar surface within granules. This mechanism is probably an important component of the small-scale dynamo supposedly acting at the solar surface and generating the quiet-Sun magnetic field.

Researchers involved:

IRSOL: O. Steiner
External: C.E. Fischer, G. Vigeesh, P. Lindner, J.M. Borrero (KIS, Freiburg), and F. Calvo (Univ. Stockholm)

Publications:

C.E. Fischer, G. Vigeesh, P. Lindner, J.M. Borrero, F. Calvo, and O. Steiner 2020, ApJ Letters 903:L10

3.2.4 Stellar magnetoconvection with RAMSES

We conduct a proof of concept for the realization of numerical simulations of compressible, stellar magnetoconvection on a cartesian grid with the code RAMSES, which takes the full compressibility of the medium into account. RAMSES is an adaptive mesh refinement, massively parallel, magneto-hydrodynamical code designed for high resolution simulations of structure formation in the Universe. We adapted the code to deal with highly subsonic turbulence, typical of stellar convective flows, by implementing a well-balanced scheme in the numerical solver. As a result, we are able to simulate a portion of a stellar convection zone, with subsequent development of a turbulent dynamo, while preserving the equilibrium profiles of the stellar interior. Moreover, we can study interaction between acoustic waves and magnetic fields, as well as the development of gravity waves, which is not achievable with stellar codes using the widely-used anelastic approximation. We ran numerical simulations on the Piz Daint supercomputer at CSCS and we performed a resolution study on the convective properties, the dynamo, and on wave propagation in a low-mass AGB star.

Researchers involved:

IRSOL: J. R. Canivete Cuissa
External: R. Teyssier (University of Zürich)

Publications:

J. R. Canivete Cuissa & R. Teyssier, in prep.

3.2.5 Propagation of internal gravity waves and the effect of oscillatory phenomena on Stokes inversion results

The solar surface is a continuous source of internal gravity waves (IGWs). We looked at naturally excited IGWs in realistic models of the solar atmosphere and studied the effect of different magnetic field topographies on their propagation. Carrying out radiation-magnetohydrodynamic simulations of a magnetic field-free and two magnetic models — one with a predominantly vertical field and one with a predominantly horizontal field — we found that IGWs in the upper solar atmosphere show upward propagation in the model with predominantly horizontal field, similar to the model without magnetic field. In contrast to that the model with predominantly vertical fields shows downward propagation. This crucial difference in the propagation direction is also present in the energy transported by waves for heights below 0.8 Mm.

Also, we employed a simulation featuring propagating MHD waves within a magnetic flux tube with a known driver and atmospheric parameters to verify if the atmospheric parameters can be returned for typical Stokes inversion procedures. We inverted two spectral lines of iron Fe I computed from the simulations using the well-known Stokes Inversions code SIR, and degraded the synthetic data to typical spatial resolutions at ground-based observatories. The output models from the inversions closely match the simulations in temperature, line-of-sight magnetic field, and line-of-sight velocity within typical formation heights of the inverted lines. Deviations from the simulations are seen away from these height regions and during the passage the waves within the line formation region.

Researchers involved:

IRSOL: O. Steiner
External: B. Fleck (ESA), P.H. Keys (Univ. Belfast), M. Roth & G. Vigeesh (KIS, Freiburg)

Publications:

G. Vigeesh, M. Roth, O. Steiner, and B. Fleck 2021, Phil. Trans. R. Soc. A 379:20200177
P.H. Keys, O. Steiner, and G. Vigeesh 2021, Phil. Trans. R. Soc. A 379:20200182

3.2.6 Acoustic-gravity wave propagation characteristics

There has been tremendous progress in the degree of realism of three-dimensional radiation magneto-hydrodynamic simulations of the solar atmosphere in the past decades. Four of the most frequently used numerical codes are Bifrost, CO5BOLD, MANCHA3D, and MURaM. We tested and compared the wave propagation characteristics in model runs from these four codes by measuring the dispersion relation of acoustic-gravity waves at various heights. We found considerable differences between the various models. The height dependence of wave power, in particular of high-frequency waves, varies by up to two orders of magnitude between the models, and the phase difference spectra of several models show unexpected features, including $\pm 180°$ phase jumps. While all the models revealed the signatures of acoustic-gravity waves in the atmosphere, with a rather similar power distribution at low frequencies, several discrepancies in the numerical results remain unexplained. To shed light on these discrepancies, we presently carry out a new benchmark study, using a common simulation box for the four simulation codes and boundary conditions as similar as possible.

Researchers involved:

IRSOL: F. Riva, O. Steiner
External: B. Fleck (ESA), M. Carlsson (RoCS, Univ. Oslo), E. Khomenko (IAC, Tenerife), M. Rempel (HAO, Boulder), G. Vigeesh (KIS, Freiburg)

Publications:

B. Fleck, M. Carlsson, E. Khomenko, M. Rempel, O. Steiner, and G. Vigeesh 2021, Phil. Trans. R. Soc. A 379:20200170

3.2.7 Verification and MPI parallelization of CO5BOLD

Bugs in simulation codes can have dramatic consequences on numerical results obtained with these tools. Therefore, an essential task in computational science concerns code verification, the process targeted to ensure that simulation codes are bug free. In this respect, we developed a suite of numerical tests to verify the correct implementation of the magnetohydrodynamic solver (HLL scheme) in CO5BOLD, the simulation code we are using at IRSOL. This suite of test problems is used to verify that the numerical solution obtained with the MHD module of CO5BOLD for more than ten one-dimensional and five two-dimension problems, involving sharp discontinuities and the propagation of Alfvén waves, converges to the correct solution when refining the computational grid. Two different versions of the tests are available, one based on the pybold python library and one on the CO5BOLD IDL routines. These tests allowed us to find and correct a number of bugs present in CO5BOLD, finally increasing the reliability of the numerical results obtained with the code. Additionally, they provided us with the opportunity of investigating how the different reconstruction schemes implemented in CO5BOLD impact the propagation of sharp discontinuities in plasma flows.

After having verified the implementation of the HLL scheme in CO5BOLD, we extended its parallelization, as well as the parallelization of the radiation transport LCFrad module, to hybrid MPI/OpenMP. It is therefore now possible to carry out radiative MHD local-box simulations with CO5BOLD on multiple nodes. We then preformed a number of strong scaling tests on the HPC system at the Euler institute and on the Piz Daint cluster at CSCS, which showed very good scalability up to several hundreds of cores.

Researchers involved:

IRSOL: F. Riva, O. Steiner

Publications:

F. Riva 2020, The CO5BOLD Quarterly Companion 17
F. Riva 2020, The CO5BOLD Quarterly Companion 18

3.2.8 Methodology for estimating the magnetic Prandtl number

A number of numerical studies focusing on turbulent dynamos was carried out in the recent past in the solar physics community. Despite that these works provided extremely useful information on many aspects of small-scale dynamo action, it is still unclear how to extrapolate these results to the Sun, in particular because of the disparate regimes of magnetic Prandtl numbers, $\mathrm{Pr_m}$, between numerical simulations and the real Sun. We therefore developed a general methodology for estimating the effective diffusivities stemming from radiative MHD simulations. The procedure is based on the method of Projection on Proper elements, initially introduced in the plasma physics community to verify plasma turbulence simulation codes. It relies on using different, higher order accuracy, numerical operators to post-process the simulation results. We then carried out a preliminary study of how solar-like local-box simulations depend on $\mathrm{Pr_m}$.

Researchers involved:

IRSOL: F. Riva, O. Steiner

3.3 Observational projects

3.3.1 SOLARNET project

This project of the Horizon 2020 research framework of the European Union started on January 2019. It aims at integrating the major European infrastructures in the field of high-resolution solar physics in view of the realization of the European Solar Telescope (EST). The project is managed by the European Association for Solar Telescopes (EAST), which was founded in 2006 and now includes members from 18 European nations. Switzerland is represented in the EAST by IRSOL. The main Swiss participant in SOLARNET is the Università della Svizzera italiana (USI), while IRSOL and

Swiss National Supercomputing Center (CSCS) are third parties. IRSOL is working on an innovative technology capable of performing high precision absolute polarimetry with low systematic errors. It is based on devices and measurement methods that has been previously applied successfully to measure the continuum polarization (Berdyugina, Gisler et al., in prep.). The goal of the project is to further develop the method for all kinds of observations where the determination of the absolute polarization value with highest accuracy is important, also for large aperture solar telescopes. In the first phase of this project, the 45 cm Gregory telescope in Locarno at IRSOL will be used as a test environment.

The technique to drastically reduce systematic errors consists of a zero-order retarder film mounted on a rotation stage in front of the IRSOL telescope. This retarder film is slowly rotated and thereby adds an additional slow modulation to the fast modulation of the modulator and ZIMPOL. We call this system the *Telescope Calibration Unit*, or *TCU* for short. The novelty consists of using a combination of measurements, which allows to correct wavelengths other than the design wavelength of the zero-order retarder film. In particular, the systematic errors in spectrograph measurements we aim to reduce with the method are the following: telescope induced polarization, cross-talk induced by the telescope, background variation in spatial and spectral dimension, fringes introduced by the FLC based modulator, and detector defects. In 2020, the technique has been theoretically described and its extended functionality investigated.

We demonstrated that measurements in many spectral lines in the visible (i.e. 450 - 650 nm) using the TCU show significantly enhanced absolute precision at IRSOL, in particular in terms of a reduction of systematic instrumental errors, including telescopic induced errors. Therefore, this method is superior to the normally used telescope matrix method to minimize telescope induced polarization cross-talk. After applying the new method, an absolute precision of a few $10^{-5}\,I$ is achieved. Although we focused on spectrograph observations, in principle there is no limitation of the new method to such systems, i.e. Fabry-Perot based imaging spectropolarimetry should also greatly benefit. This we plan to test in the future. Another relevant performance criterion is the spatial resolution reduction when the TCU is used, which was briefly investigated. Although a final quantification of this reduction is still work in progress, we find that using the TCU noticeably reduces the spatial resolution.

For the science operation, the new method will increase the achievable polarimetric accuracy, but at the same time will reduce the polarimetric efficiency. Further, the slow modulation will not allow to use this method in science cases where high temporal resolution is crucial. The first point can be improved by using a larger aperture solar telescope. Also the problem with the spatial resolution can be improved by placing a retarder of much better optical quality close to a converged beam but still in front of polarizing elements, as we plan to do at the GREGOR telescope in Tenerife in 2021.

By December 2020, the first (out of two) SOLARNET report was delivered to the SOLARNET workpackage leader.

Researchers involved:

IRSOL: F. Zeuner, D. Gisler, M. Bianda, R. Ramelli

3.3.2 Synoptic program to measure the evolution of the photospheric magnetic field during a solar cycle

Since 2007 we have been carrying out a synoptic program in order to determine if the magnetic flux of the quiet photosphere varies with the solar cycle. With this goal in mind, we apply a differential

Hanle effect technique, based on observations of scattering polarization in C2 molecular lines around 514.0 nm, generally taken every month. Our results now span more than a complete solar cycle. In 2020 observations have been done also with the TCU device (see 3.3.1). This allows to strongly reduce the systematic errors in the absolute measurement of the polarization signals and thus should allow to better apply the differential Hanle effect technique.

Researchers involved:

IRSOL: D. Gisler, F. Zeuner, R. Ramelli, M. Bianda

External: S. Berdyugina (KIS)

3.3.3 2D imaging spectropolarimetry of prominences in He I D_3

The results of the master work of Riccardo Di Campli performed in 2017 were published. A technique that permits 2D spectropolarimetry using our Fabry Perot filter system together with the spectrograph and ZIMPOL is described. The results obtained observing a prominence are reported. Using an inversion code the magnetic map of the prominence is calculated. The amplitude of the magnetic field and its orientation confirms further result obtained with spectrographic techniques.

Researchers involved:

IRSOL: R. Ramelli, M. Bianda, I.; S.K. Dhara, L. Belluzzi

External: R. Di Campli, I. Furno (Swiss Plasma Center, EPFL)

Publications:

Di Campli et al. 2020, A&A,644, 89

3.3.4 Parker perihelion campaign

During the Parker Solar Probe 4th Perihelion Campaign, an observational afford to combine many observatories for context images while the NASA space mission Parker Solar Probe encountered its fourth perihelion, IRSOL joint the international team with spectropolarimetric observations in January 2020. The observations were carried out in the frequency range around 4227 Å (Ca I line), using the Zurich Imaging Polarimeter (ZIMPOL) at the IRSOL telescope in Switzerland. The radiation in the Ca I line core is sensitive to the thermodynamic properties of the mid chromosphere (about 1000 km) while the line wings provide information on deeper atmospheric layers. The neighboring lines (almost all iron lines) are photospheric. Since Parker Solar Probe takes in-situ measurements, their interpretation heavily relies on context data provided by other instruments. The aim of the IRSOL observations are to provide unprecedented information about the tangled magnetic fields in the chromosphere as well as in the photosphere, using the magneto-optical effects and the Hanle effect in the Ca I line.

The IRSOL data has been reduced and made available on the IRSOL website. Additionally, a video tutorial about these data has been presented at the WHPI "Show and Tell" days occurred on 14th-15th September, 2020.

Researchers involved:

IRSOL: M. Bianda, F. Zeuner, E. Capozzi, R. Ramelli

3.4 Miscellaneous, science

Prof. Jan Olof Stenflo besides his solar physics works is exploring new research fields. José Roberto Canivete Cuissa worked on a project lead by Prof. Dr. P. Saha, which was part of the Astrophysical Thinking course at the Institute for Computational Science (UZH) and that lead to a publication.

3.4.1 Origin of the cosmological constant

The so-called cosmological constant is a parameter that is needed to model the observed accelerated expansion of the universe. In standard cosmology it is interpreted as a new kind of field, "dark energy", whose energy density does not decrease as the universe expands, in contrast to the energy densities of matter and radiation. By some coincidence it happens to be of the same order of magnitude as the present energy density of matter. Thus, in the view of standard cosmology, our epoch in cosmic history is singled out as a time when this mysterious form of energy is becoming the dominant form that will drive an inflationary, exponential expansion, which will last for all eternity. In contrast, J.O. Stenflo has recently shown that the cosmological constant can instead be explained as a kind of integration constant, which arises because the age of the universe is finite. Since the magnitude of the cosmological constant is then tied to the value of the current age, in proportion to the square of the inverse age, its magnitude will decline as the universe grows older, and it will not drive any inflationary expansion. Our epoch in cosmic history is not singled out as something special. It is shown how the link to the so-called conformal age of the universe can be made unique, which allows the theory to predict the value of the cosmological constant without the need for any adjustable parameters. The so predicted value of the cosmological constant is found to agree with the observed value with a precision of about 2%.

Researchers involved:

IRSOL: J.O. Stenflo

Publications:

- **Stenflo, J. O.**: 2020, *Nature of dark energy*, In: M.L. Smith (ed.), *Cosmology 2020–The Current State*, London, DOI: 10.5772/intechopen.91442, pp. 55–75, URL: www.intechopen.com/books/cosmology-2020-the-current-state/nature-of-dark-energy
- **Stenflo, J. O.**: 2020, *Cosmological constant caused by observer-induced boundary condition*, J. Phys. Commun., **4**, 105001

3.4.2 Towards a polarization prediction for LISA via intensity interferometry

The Laser Interferometer Space Antenna (LISA), or a similar mission, should be able to detect low frequency gravitational waves (GW) from some compact Galactic binaries, also known as LISA verification binaries. From the measured properties of these binaries, it is possible to predict the frequency and the amplitude of the GW, but not the polarization. This is because such binaries cannot be resolved by current telescopes, and their orientation in the sky (inclination and position angle) is needed for a full-fledged prediction.
We suggest to use km-scale optical intensity interferometry to measure the tidal stretching of one companion of a LISA verification binary, hence determine the elusive binary orientation and predict the GW polarisation. We estimate that the hot helium subdwarf of the CD–30°11223 binary will

be tidally stretched by 6% by its white dwarf companion. We estimate that using the Very Large Telescope (VLT) and the Extremely Large Telescope (ELT) together for intensity interferometry, and equipping them with kilopixel sub-ns single-photon counters, would allow to measure the orientation to $\pm 1^\circ$ at 2σ confidence in 24 hours of observation.

Researchers involved:

IRSOL: J. R. Canivete Cuissa

External: S. Baumgartner, M. Bernardini, H. de Laroussilhe, A. M. W. Mitchell, B. A. Neuenschwander, P. Saha, T. Schaeffer, D. Soyuer, L. Zwick (University of Zürich)

Publications:

S. Baumgartner, M. Bernardini, **J. R. Canivete Cuissa**, H. de Laroussilhe, A. M. W. Mitchell, B. A. Neuenschwander, P. Saha, T. Schaeffer, D. Soyuer, and L. Zwick, 2020, MNRAS, 498, 4577.

3.4.3 ESA call for White Papers for Voyage 2050 long-term plan

In 2019, Dr. Belluzzi and Dr. Alsina Ballester participated in the preparation of a proposal in response to a call by ESA for White Papers for the *Voyage 2050* long-term plan. The scientific focus of the proposal, entitled "Magnetic Imaging of the Outer Solar Atmosphere" (MImOSA), was the characterization and measurement of the magnetic fields present in the outer solar atmosphere. The work, led by Dr. Hardi Peter from MPS, received appreciation and was selected for an oral presentation in Madrid in October 2019. The evaluation of the proposals has suffered a significant delay due to the COVD-19 pandemic and is still ongoing. The release of the Voyage 2050 public report is expected in 2021. In July 2020, the proposal was submitted as a paper to be published in a series of special issues of the journal Experimental Astronomy. The referee report was received few days before this document was prepared.

Researchers involved:

IRSOL: L. Belluzzi, E. Alsina Ballester

External: MImOSA team (Europe)

Publications:

H. Peter, E. Alsina Ballester, V. Andretta, F. Auchère, L. Belluzzi, A. Bemporad, D. Berghmans, E. Buchlin, A. Calcines, L.P. Chitta, K. Dalmasse, T. del Pino Alemán, A. Feller, C. Froment, R. Harrison, M. Janvier, S. Matthews, S. Parenti, D. Przybylski, S.K. Solanki, J. Štěpán, L. Teriaca, & J. Trujillo Bueno, *Magnetic Imaging of the Outer Solar Atmosphere (MImOSA) - Unlocking the driver of the dynamics in the upper solar atmosphere*, Exp. Astr. [submitted]

3.5 Specola Solare Ticinese

Scientific work at Specola Solare Ticinese is focused on the determination of the international Sunspot Number (SSN) released by the SILSO World Data Center at the Royal observatory in Brussels, for which Specola is the international reference station. The experience of Sergio Cortesi, who worked under the direction of Max Waldmeier starting in 1957 till 1980, gave continuity to the counting method defined in Zurich by Rudolf Wolf in the mid 1800s. This know-how has been transmitted to Marco Cagnotti.

In 2020, 291 sunspot drawings were made; the drawings and the calculated Wolf number can be found on the web (`http://www.specola.ch`).

IRSOL staff collaborates with Specola for outreach activities and, when required, for making the solar drawings and performing their reduction. Ramelli acts also as Web Master for the Specola web pages.
The Sunspot Number (SSN) time series is now included in the new implementation plan of the Global Climate Observing System (GCOS).

In particular the Swiss GCOS office at MeteoSwiss finances a project coordinated by Ramelli and done in collaboration with ETH Zurich University Archives for the safe and long term archiving and digitization of the observational data produced by Specola Solare Ticinese.

The main project milestones achieved at Specola in 2020:

1. Completed metadata and signatures of the drawings from 1981 to 2019
2. Transport of the sunspot drawings and other documents to ETH Zurich University Archives (21st August)
3. Completed and checked Sunspot Group Database from 1981 to now.
4. Developed a WEB interface to publish the Sunspot Group Database at `https://sunspots.irsol.usi.ch/db/`. (Main task of the civil service carried out by Christian Skorski).
5. Elaboration of the Sunspot drawings with the software *Digisun* from 1957 to 1963.

Researchers involved:

IRSOL-Specola: M. Cagnotti, S. Cortesi, R. Ramelli

External: F. Clette (SILSO, Brussels), S. Bechet (SILSO, Brussels), M. Gatti (Bisuschio, Varese)

3.6 Education

3.6.1 Master and bachelor

MS Andrea Francesco Battaglia has carried out his master thesis under the title “Origin and evolution of magnetic swirls in numerical simulations of the solar atmosphere”. The thesis was supervised by Dr. O. Steiner at IRSOL and directed by Prof. Dr. L. Harra of ETHZ and PMOD Davos and was submitted to ETHZ on March 23, 2020.

3.6.2 Internship and outreach program

At IRSOL we offer young students (secondary and high school) the opportunity to visit a research institute, which can generate interest for a scientific educational path. Every year we give to young secondary school students the opportunity to perform a one day stage before they start the high school. In collaboration with a local company we offered a one day stage at IRSOL to secondary school students of a school in Ascona reporting the best marks in scientific courses. Moreover, we offer support for maturity works dedicated to astronomical topics (see 8.4).

In 2017 the cantonal administration of Canton Ticino started the program “Estage”, intended to better connect students of the Swiss Italian area with local industries and research institutes promoting stages announced on a web page (`www4.ti.ch/can/oltreconfiniti/dal-1990-a-oggi/estage/`). This year a student participated.

Martina Mongillo. From 27-07-2020 to 27-08-2020 the physics bachelor student Martina Mongillo from the University of Bern worked at IRSOL during the internship project Estage. She contributed to the development of the Mueller matrix determination of the IRSOL Gregory-Coudé telescope. Her tasks focused primarily on the development of scripts to analyze and visualize scientific data with the programming language python. She also assisted observations at the telescope.

Researchers involved:

IRSOL: F. Zeuner, D. Gisler

With “L’ideatorio”, Università della Svizzera italiana, we submitted an Agorà proposal to SNF under the title ”il Sole”.

IRSOL promotes an outreach program together with Specola Solare Ticinese, organizing observation events supervised by an astronomer.

One of the work packages of the H2020 project PRE-EST is devoted to outreach. We collaborate to this project.

4 INSTRUMENTAL WORK

4.1 ZIMPOL project

4.1.1 Preparation and installation of a ZIMPOL3 camera at OMEL

The Optical Materials Engineering Laboratory (OMEL) at ETH Zurich has started a collaboration with IRSOL to apply ZIMPOL to study Raman Optical Activity (ROA). ROA is the study of the circularly polarized component in Raman scattered light. This technique provides valuable insights into molecular chirality and the biomolecular structure. The chirality of molecules is of critical importance because it determines a molecule’s biological activity. This makes molecular chirality of key importance both in academic research, and in the chemistry and biotech industries.

IRSOL supports this project by providing a ZIMPOL camera system and our knowledge using this instrument. In the two previous years OMEL has already used our former ZIMPOL2 system for there work but the live time of this instrument was at the end and IRSOL could not provide any maintenance. Therefore in 2020 at IRSOL we prepared one of our current ZIMPOL3 camera for using the ZIMPOL2 sensors. We carefully calibrated the camera and determined their properties. In October the system was installed at OMEL and adapted for the ROA application.

4.1.2 Instrument software

The instrument software is based on a distributed server client concept which is very flexible and is used for all kind of instruments at IRSOL. In the previous year a core part of the instrument software, the Command Stream Interpreter (CSI) has been new implemented in Python. At beginning of 2020 the new CSI got into operation and has been further improved during the year. The software is now running very stable. The project was again greatly supported by Peter Steiner the retired ETH engineer who originally developed the software for ZIMPOL.

A new telescope server has been developed. It replaces several old programs to control the telescope (motors and encodes), parts of the active guiding system (PIG) and coordinate calculations. In addition the old LabView GUI has been replaced by our standard GUI client program.

4.2 Cooperation with KIS for the VTF

The Visible Tunable Filter (VTF) is a Fabry-Perot based spectro-polarimeter. It will be a first light instrument for DKIST, designed for high spatial resolution 2D imaging spectropolarimetry and spectroscopy. It is currently under construction at KIS, and on-site installation and commissioning is planned for 2022. Due to our good expertise in fast polarization modulator technology KIS asked IRSOL for support. IRSOL agreed to a collaboration and provides a certain amount of manpower to this project. In return and according to the amount of work done in the construction phase, IRSOL will be granted observing time with VTF at DKIST. 2020 IRSOL contributed the following tasks to VTF:

- Support of the design of a petaprism housing
- Final assembly of the pentaprism

4.3 The CALLISTO project

The CALLISTO spectrometer is a programmable heterodyne receiver designed 2006 in the framework of IHY2007 and ISWI by Christian Monstein (PI) as member of the former Radio Astronomy Group(RAG) at ETH Zurich, Switzerland. Since 2019 IRSOL is the host Institute of the CALLISTO project with Christian Monstein as an affiliated staff member. The main applications are observation of solar radio bursts for astronomical science, education, outreach and citizen science as well as rfi-monitoring. Many CALLISTO instruments have already been deployed worldwide and form together the e-Callisto network. CALLISTO is able to continuously observe the solar radio spectrum for 24h per day through all the year. Data from individual instruments are automatically uploaded to the central server at University of Applied Sciences (FHNW) in Brugg/Windisch.

In 2020 eleven new spectrometers as part of the e-Callisto network have been delivered to the following locations: Indian Institute of Astrophysics (India), North West University (South Africa), Egypt-Japan University of Science and Technology (Egypt), Earth Science at Ibaraki University (Japan), Deutsches Zentrum für Luft- und Raumfahrt (Germany), Kodaikanal Solar Observatory (India)

Several stations were able to detect their first light solar radio burst: Centre de recherche en astronomie, astrophysique et géophysique (Algeria), Private Radio Observatory Landschlacht (Switzerland), Astronomical Society of South Australia (Australia), Metsähovi Radio Observatory (Finland), Norwegian Space Centre (Norway), Embry-Riddle Aeronautical University (Arizona,USA), Observatorio Astronómico Los Molinos (Uruguay), Deutsches Zentrum für Luft- und Raumfahrt (Germany)

In 2020 we finally managed to register all CALLISTO spectrometers at ITU-level as Space Weather Sensor System. This helps the individual hosts to get some protection on frequencies which are reserved for radio astronomy.

Researchers involved:

IRSOL: C. Monstein

Publications:

Mahender, Aroori; Sasikumar Raja, K; Ramesh, R; Panditi, Vemareddy; Monstein, Christian; Ganji, Yellaiah, 2020, Solar Physics, Volume 295, Issue 11

Wan Mokhtar, W Z A; Hamidi, Z S; Abidin, Z Z; Ibrahim, Z A; Monstein, Christian 2020, Indian Journal of Physics

Pauzi, F A M; Abidin, Z Z; Guo, S J; Gao, G N; Dong, L; Monstein, Christian, 2020, Solar Physics, Volume 295, Issue 3, article id.42

5 TECHNICAL WORK

5.1 New IT concept

Thanks to the affiliation with USI, we can now have access to the IT services of the university. A new connection based on an optical cable has been installed by Cablecom (see 5.4). The line connects IRSOL directly with SUPSI-DFA in Locarno, and from there to USI.

The existing network cabling topology had to be modified, in accordance with the requirements given by the USI IT system administration. Part of the existing wiring at the institute, and the optical fiber connection between the observatory and the main building could be maintained. New switches and WLAN antennas have been ordered through USI. They will be maintained and configured directly by USI.

Delays in the delivery of hardware (due to the pandemic situation) shifted the installation of the new IT network system at IRSOL to March 2021.

For the onsite IT-support we started a collaboration with the outsourcing company Ticimatica.

The WEB hosting of the IRSOL webpages and related MySQL databases has been transferred to the servers at USI. This required to update some scripts. The civilist Christian Skorski provided help for that.

5.2 Computers

To replace some old instruments computers three new ones has been purchased. They have identical hardware and the same Linux OS has been installed to simplify usage and maintenance.

A further PC to be used for guests was prepared during the civil service period by Christian Skorsky.

5.3 Mechanical worshop

The work of Ezio Bonetti, civil service, was dedicated to rearrange the mechanical workshop and performing some maintenance works to the telescope.

5.4 Infrastructure work

Thanks to the additional funds obtained from an inheritance we could continue performing renovation works at IRSOL.

The access road to IRSOL was the original one constructed 70 years ago, and was requiring a new asphalt layer. We could take this opportunity combining different required works.

- Providing an optical fiber connection to the institute. The connection was till then assured by old copper wires that limited the speed connection .
- For technical reasons, the institute was not yet connected to the dark water canalization. Thanks the collaboration of the municipality of Orselina, a solution could be found.
- The power grid company SES is renovating the distribution installing new underground lines; they could take advantage from our road works.
- The access road was thus opened to install underground canalization and tubes required for the above mentioned works, included a spare connection for unexpected tasks. Some reinforcements works were performed, and in 2021 the road is newly asphalted

That also permitted to fix some minor issues.

6 WORKS FORESEEN IN 2021

- **Università della Svizzera italiana, USI**

  in 2021 the affiliation of IRSOL with USI will be official. The affiliation agreement, after a positive conclusion of the discussions with the federal foundation control office in Bern, will be signed between USI and FIRSOL.

  IRSOL will be partner of the new Euler institute at USI. We are very interested to optimize our contribution in this important project.

- **Collaboration with SUPSI**

  The maintenance and development of ZIMPOL will be now ensured by SUPSI. Strategic decisions about how to proced will be taken.

  A strategic plan is required to develop a new generation of polarimeters based on the ZIMPOL technology

- **Collaboration with KIS**

  With the Leibnitz Institute of Solar Physics, KIS, we have a long ongoing collaboration that also includes sharing of researchers, and the director of KIS as co-director of IRSOL. The technical cooperations can be summarized in the availability of ZIMPOL at GREGOR, in the cooperation of D. Gisler to the project VTF for DKIST, and in the construction of a telescope calibration unit version for GREGOR, developed in the SOLARNET project (see chapter 3.3.1)

- **Development of the scientific program**

  The topics already developed and described in section 3 will be continued.

- **Infrastructure**

  The institute IT system will be completed.

  A fire alarm system will be installed.

  Some refreshments in a bath are foreseen

7 SCIENTIFIC ACTIVITY

7.1 Visits

12/08 Helène Frish, Uriel Frisch, Nice university, France

23-27/09 Vigeesh Gangadharan, Leibniz Institut für Sonnenphysik, KIS, Freiburg, Germany

7.2 Visits to other institutes

18/02 Bianda, Gisler, Ramelli, ETHZ

09/09 Steiner, Uni-ZH, PhD Committee Meeting

7.3 Participation to workshops, meetings, schools and talks

21-23/01 M. Bianda, P. Benedusi (USI), Prague EAST General Assembly, PRE-EST Board meeting, SOLARNET General Assembly;

03-06/02 O. Steiner, J. R. Canivete Cuissa, International Space Science Institute (ISSI), "The Nature and Physics of Vortex Flows in Solar Plasmas". Talks: *On the generation and evolution of swirls in the solar atmosphere* and *Vortex evolution in the solar atmosphere: a dynamical equation for the swirling strength*;

10-11/02 O. Steiner, Royal Society Theo Murphy discussion meeting "High resolution wave dynamics in the lower solar atmosphere" (online);

17/03, 04/06, 02/09 R. Ramelli, Swiss SCOSTEP committee meeting, (online).

25/06 L. Belluzzi, E. Alsina Ballester, Swiss Solar Science day, (online): "NLTE RT modeling of spectral line polarization with partial frequency redistribution"

25/06 C. Monstein, Swiss Solar Science day, (online): "CALLISTO instrument and the e-Callisto network"

25/06 M. Bianda, Swiss Solar Science day, (online): ”Interactions with the EST project”

25/06 O. Steiner, Swiss Solar Science day, (online): ”Computational Solar Physics at IRSOL: recent past and present work”

25/06 J.R. Canivete Cuissa, Swiss Solar Science day, (online): ”A dynamical equation for the swirling strength and application of it to the solar atmosphere.”

25/06 R. Ramelli, Swiss Solar Science day, (online): ” IRSOL observational programs and instrumentation”

25/06 F. Zeuner, Swiss Solar Science day, (online): ”The IRSOL project in SOLARNET”

14-15/09 R. Ramelli, F. Zeuner, E. Capozzi, WHPI “Show and Tell days” (online): ”IRSOL contribution for the Parker campaign”

02/10 E. Alsina Ballester, invited speaker at the Weekly Astronomy Seminars (Stockholm University, Sweden). Talk: *Magnetic sensitivity of the H* I *Ly-α scattering polarization wings in the solar disk radiation* (online).

12/10 O. Steiner, 1st Science Data Center (SDC) workshop, KIS, Freiburg. Talk: *Simulation Data: present status, requirements, and visions* (online);

29/10 M. Bianda, 4th Swiss SCOSTEP workshop (online): ”News about the European Solar Telescope”

30/10 A. F. Battaglia, J. R. Canivete Cuissa, 4th Swiss SCOSTEP workshop (online): ”Imprints of torsional Alfvén pulses in magnetic swirls”

30/10 E. Capozzi, 4th Swiss SCOSTEP workshop (online): ”Magneto-optical effects in the wings of the Ca I 4227 A line ”

30/10 F. Zeuner, 4th Swiss SCOSTEP workshop (online): ”Absolute high precision solar polarimetry”

30/10 E. Alsina Ballester, 4th Swiss SCOSTEP workshop (online): ”Radiative transfer modeling of spectral line polarization considering complex atomic models”

30/10 G. Janett, 4th Swiss SCOSTEP workshop (online): ”Radiative transfer modeling of spectral line polarization accounting for angle-dependent PRD effects”

7.4 Participation in scientific committees

- *L. Belluzzi:* Member of the Science Advisory Group (SAG), appointed to update the Science Requirement Document (SRD) for the European Solar Telescope (EST).
- *O. Steiner:* Member scientific advisory committee of the Rosseland Center for Solar Physics (RoCS) of the University of Oslo.
- *O. Steiner:* Member Time Allocation Committee (TAC) for the SOLARNET trans-national access programme for observing and high performance computing time.

- *M. Bianda* Organizing Committee Member of Commission E1 Solar Radiation and Structure
- *R. Ramelli*: member of the Swiss SCOSTEP committee
- *C. Monstein*, Member of steering committee of International Space Weather Initiative (ISWI) at United Nations Office of Outer Space Affairs (UNOOSA) in Vienna, Austria
- *C. Monstein*, Member of Committee on Radio Astronomy Frequencies (CRAF)
- *C. Monstein*, Member of Committee on Space Research (COSPAR)

7.5 Awards

- Edith Alice Müller Award 2020

  The PhD Prize of the Swiss Society for Astrophysics and Astronomy (SSAA) was attributed ex aequo to:

  Dr. Ewelina Obrzud (UniGE and CSEM) for her thesis on *High repetition rate laser frequency combs for astronomical spectrograph calibration*

  and

  Dr. **Gioele Janett** (IRSOL) for his thesis on *Numerical Methods for the Transfer Equation of Polarized Radiation*

  As a note: Ewelina Obrzud in 2013 carried out a practical work (TP) at IRSOL with the title: "Determining differential rotation of the Sun"

- NASA's Group Achievement Honor Award

  The Chromospheric LAyer SpectroPolarimeter (CLASP2) Team (of which Dr. **L. Belluzzi** and Dr. **E. Alsina Ballester** are members) received the NASA's Group Achievement Honor Award "for outstanding execution of the Chromospheric LAyer SpectroPolarimeter sounding rocket mission, which launched from White Sands Missile Range on April 11, 2019"

8 ATTIVITÀ DIVULGATIVA

8.1 Visite guidate, visite di cortesia

La situazione particolare ha drasticamente ridotto questa attività.

8.2 Stages informativi

20/08 stage premio per le migliori note in scienze in 4^a media al Collegio Papio (DFD Solutions SA Tecnologia e sistemi di Sicurezza - IRSOL): Aline Bianda, Riccardo Zucconi

8.3 Organizzazione di eventi

Nel 2020 la situazione pandemica ha nettamente influenzato questa attività.

8.4 Lavori di Maturità seguiti all'IRSOL

I lavori di maturità svolti da Daniel Panero e Luca Rivera nel 2019 e completati in gennaio 2020 sono stati premiati con il primo e il terzo premio al concorso Fioravanzo 2020.

8.5 Presenza nei media

8.5.1 Radio

19.02 Michele Bianda, Rete 1, Millevoci, "Un viaggio attorno al sole con Solar Orbiter"

8.5.2 Televisione

8.08 Renzo Ramelli, Teleticino, Ticinonews, "Meteore e notte di San Lorenzo" (intervista in diretta)

8.5.3 Articoli apparsi sulla stampa

11.02 La Regione, "Nuova luce sul Sole"

19.02 Corriere del Ticino, "L'Istituto ricerche solari sale in cattedra"

03.03 Cooperazione, "Non si limita a illuminarci"

8.5.4 Articoli apparsi online

19.02 USI - NOtizie ed eventi, "Approvata l'affiliazione dell'Istituto di ricerche solari Locarno all'USI" e "IRSOL becomes an affiliated institute of USI" (www.usi.ch/it/feeds/12920)

19.02 RSI, "L'IRSOL di Locarno è ora universitario" (www.rsi.ch/news/ticino-e-grigioni-e-insubria/L'IRSOL-di-Locarno-è-ora-universitario-12757701.html)

08.11 ESPD, "ESPD Media of the Month: November 2020", vincitrice Franziska Zeuner (www.eps.org/blogpost/739454/361051/ESPD-Media-of-the-Month-November-2020)

9 PUBLICATIONS

9.1 Appeared in 2020

9.1.1 Appeared in peer reviewed journals

Afandi, N.Z.M., Sabri, N.H., Umar, R., **Monstein, C.**: 2020, *Burst-Finder: burst recognition for E-CALLISTO spectra*, Indian Journal of Physics **94**, 947

Baumgartner, S., Bernardini, M., **Canivete Cuissa, J.R.**, de Laroussilhe, H., Mitchell, A.M.W., Neuenschwander, B.A., Saha, P., Schaeffer, T., Soyuer, D., Zwick, L.: 2020, *Towards a polarization prediction for LISA via intensity interferometry*, Monthly Notices of the Royal Astronomical Society **498**, 4577

Canivete Cuissa, J.R., **Steiner, O.**: 2020, *Vortices evolution in the solar atmosphere. A dynamical equation for the swirling strength*, A&A **639**, 118

Capozzi, E.., **Ballester, E.A.**, **Belluzzi, L.**, **Bianda, M.**, **Dhara, S.K.**, **Ramelli, R.**: 2020, *Observational indications of magneto-optical effects in the scattering polarization wings of the Ca I 4227 Å line*, A&A **641**, 63

Di Campli, R., **Ramelli, R.**, **Bianda, M.**, Furno, I.; **Kumar Dhara, S.**, **Belluzzi, L.**: 2020, *Imaging spectropolarimetry for magnetic field diagnostics in solar prominences*, A&A **644**, 89

Fischer, C.E., Vigeesh, G., Lindner, P., Borrero, J.M., Calvo, F., **Steiner, O.**: 2020, *Interaction of Magnetic Fields with a Vortex Tube at Solar Subgranular Scale*, ApJ Letters **903**, L10

Mahender, A. Sasikumar R.K.; Ramesh, R.; Panditi, V.; **Monstein, C.**, Ganji, Y.: 2020, *A Statistical Study of Low-Frequency Solar Radio Type III Bursts*, Solar Physics **295**, 153

Nagendra, K.N., Sowmya, K., Sampoorna, M., **Stenflo, J.O.**, Anusha, L.S.: 2020, *Importance of Angle-dependent Partial Frequency Redistribution in Hyperfine Structure Transitions Under the Incomplete Paschen-Back Effect Regime*, 2020, ApJ **898**, 49

Pauzi, F.A.M.; Abidin, Z.Z.; Guo, S.J.; Gao, G.N.; Dong, L.; **Monstein, C.**: 2020, *Investigation into CME Shock Speed Resulting from Type II Solar Radio Bursts*, Solar Physics **295**, 42

Prieto, M., Gordo, J.B., Rodríguez-Pacheco, J., Martínez, A., Sánchez, S. Russu, A., **Monstein, C.**, Fernández, R.: 2020, *Increase in Interference Levels in the 45 - 870 MHz Band at the Spanish e-CALLISTO Sites over the Years 2012 and 2019*, Solar Physics **295**, 42

Stenflo, J.O.: 2020, *Cosmological constant caused by observer-induced boundary condition*, Journal of Physics Communications **4**, 105001

Stenflo, J.O.: 2020, *Nature of dark energy*, in: M.L. Smith (ed.), "Cosmology 2020–The Current State", DOI: 10.5772/intechopen.91442, pp. 55–75, www.intechopen.com/books/cosmology-2020-the-current-state/nature-of-dark-energy

Zeuner, F., Manso Sainz, R., Feller, A., van Noort, M., Solanki, S.K., Iglesias, F.A., Reardon, K., Martínez Pillet, V.: 2020, *Solar Disk Center Shows Scattering Polarization in the Sr I 4607 Å Line*, The Astrophysical Journal **893**, L44

9.1.2 Appeared in proceedings or ArXiv

Alsina Ballester, E., **Belluzzi, L.**, & Trujillo Bueno, J.: 2019, *The Transfer of Resonance Line Polarization with PRD in the General Hanle-Zeeman Regime*, in: L. Belluzzi et al. (eds.), "Solar Polarization 8", ASP Conf. Ser., **526**, 119

Bianda, M., **Ramelli, R.**, **Gisler, D.**, **Belluzzi, L.**, **Carlin, E.S.**: 2019, *Second Solar Spectrum observations with ZIMPOL*, in: L. Belluzzi et al. (eds.), "Solar Polarization 8", ASP Conf. Ser. **526**, 223

Ishikawa, R. et al. (28 co-authors, including **Alsina Ballester, E.** and **Belluzzi, L.**): 2019, *Comparison of Scattering Polarization Signals Observed by CLASP: Possible Indication of the Hanle Effect*, in: L. Belluzzi et al. (eds.), "Solar Polarization 8", ASP Conf. Ser., **526**, 305

Janett, G., **Steiner, O.**, **Belluzzi, L.**: 2019, *Numerical methods for the radiative transferequation of polarized light*, in: L. Belluzzi et al. (eds.), "Solar Polarization 8", ASP Conf. Ser. **526**, 133

Landi Degl'Innocenti, E., & **Belluzzi, L.**: 2019, *Relaxation Phenomena Due to Collisions with Neutral Perturbers in Hyperfine Structure Multiplets*, in: L. Belluzzi et al. (eds.), "Solar Polarization 8", ASP Conf. Ser. **526**, 29

McKenzie, D.E. et al. (19 co-authors, including **Alsina Ballester, E.** and **Belluzzi, L.**): 2019, *CLASP2: The Chromospheric LAyer Spectro-Polarimeter*, in: L. Belluzzi et al. (eds.), "Solar Polarization 8", ASP Conf. Ser. **526**, 361

Ramelli R., **Bianda M.**, **Berdyugina S.V.**, **Belluzzi L.**, Kleint L.: 2019, *Measurement of the evolution of the magnetic field of the quiet photosphere during a solar cycle*, in: L. Belluzzi et al. (eds.), "Solar Polarization 8", ASP Conf. Ser. **526**, 283

Ramelli, R., **Bianda, M.**, Setzer, M., Enegelhard, M., **Paglia, F.**, **Stenflo, J.O.**, Küveler, G., Plewe, R.: 2019 *Atlas of the Solar Intensity Spectrum and its Center-to-Limb Variation*, in: L. Belluzzi et al. (eds.), "Solar Polarization 8", ASP Conf. Ser. **526**, 287 https://it.overleaf.com/project/608

Sowmya, K., **Nagendra, K.N.**, Sampoorna, M., **Stenflo, J.O.**: 2019, *Partial frequency redistribution theory with Paschen-Back effect: Application to Li I 6708 Ålines*, in L. Belluzzi et al. (eds.), "Solar Polarization 8", ASP Conf. Ser. **526**, 43

Stenflo, J.O: 2019, *The Kramers-Heisenberg coherency matrix*, in: L. Belluzzi et al. (eds.), "SolarPolarization 8", ASP Conf. Ser. **526**, 49

Stenflo, J.O: 2019, *Summary talk: Looking ahead*, in: L. Belluzzi et al. (eds.), "Solar Polarization 8", ASP Conf. Ser. **526**, 369

Supriya, H.D., Sampoorna, M., **Nagendra, K.N.**, **Stenflo**, J.O., Ravindra, B.: 2019, *Effects oflower-level polarization and partial frequency redistribution on Stokes profiles*, in: L. Belluzzi et al. (eds.), "Solar Polarization 8", ASP Conf. Ser. **526**, 61

Peter, H., **Alsina Ballester, E.**, Andretta, V., Auchere, F., **Belluzzi, L.**, et al. (19 co-authors): 2021, *Magnetic Imaging of the Outer Solar Atmosphere (MImOSA): Unlocking the driver of the dynamics in the upper solar atmosphere*, arXiv:2101.01566

9.1.3 Books

Belluzzi, L., Casini, R., Romoli, M., & Trujillo Bueno, J. (eds.): 2019, *Solar Polarization 8*, ASP Conf. Ser. 526

9.2 In press or already published in 2021

Battaglia, A., **Canivete Cuissa, J.R.**, Calvo, F., Bossart, A.A., **Steiner, O.**: 2021, *The Alfvénic nature of chromospheric swirls*, A&A **649**, A121

Fleck, B., Carlsson, M., Khomenko, E., Rempel, M., **Steiner, O.**, Vigeesh G.: 2021, *Acoustic-gravity wave propagation characteristics in three-dimensional radiation hydrodynamic simulations of the solar atmosphere*, Phil. Trans. R. Soc. A 379:20200170

Ishikawa, R. et al. (27 co-authors, including **Belluzzi, L.** and **Alsina Ballester, E.**): 2021, *Mapping Solar Magnetic Fields from the Photosphere to the Base of the Corona*, Sci. Ad., 7, 8

Keys, P.H., **Steiner, O.**, Vigeesh, G.: 2021, *On the effect of oscillatory phenomena on Stokes inversion results*, Phil. Trans. R. Soc. A 379:20200182

Paganini, A., Hashemi, B., **Alsina Ballester, E.**, **Belluzzi, L.**: 2021, *Fast and accurate approximation of the angle-averaged redistribution function for polarized radiation*, A&A, **645**, 4

Wan Mokhtar, W.Z.A., Hamidi, Z.S., Abidin, Z.Z., Ibrahim, Z.A., **Monstein, C.** "Data background levels of the metre and decimetre wavelength observations by E-CALLISTO network: the Gauribidanur and Greenland sites": 2021, Indian Journal of Physics **95**, 1051

Vigeesh, G., Roth, M., **Steiner, O.**, Fleck, B.: 2021, *On the influence of magnetic topology on the propagation of internal gravity waves in the solar atmosphere*, Phil. Trans. R. Soc. A 379:20200177

9.3 Theses

Battaglia, A.: 2020, Origin and evolution of the magnetic swirls in numerical simulations of the solar atmosphere, Master's thesis, ETHZ

9.4 Other publications

Fischer, C.E., Vigeesh, G., Lindner, P., Borero, J.M., Calvo, F., **Steiner, O.**: 2020, *Interaction of Magnetic Fields with a Vortex Tube at Solar Subgranular Scale*, in: H.-G. Ludwig (ed.), The CO5BOLD Quarterly Companion **18**

Riva, F.: 2020, *Bug report*, in: H.-G. Ludwig (ed.), The CO5BOLD Quarterly Companion **17**

Riva, F.: 2020, *Hybrid OpenMP/MPI parallelization*, in: H.-G. Ludwig (ed.), The CO5BOLD Quarterly Companion **18**

Steiner, O.: 2020, *Acoustic-gravity wave propagation characteristics: Comparison with different codes*, in: H.-G. Ludwig (ed.), The CO5BOLD Quarterly Companion **17**

9.5 Atlas and scientific data on our website

On the page `http://www.irsol.usi.ch/data-archive` one can find several atlas in digital form.