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PROF. DR MILEVA PRVANOVIĆ - HER CONTRIBUTION TO DIFFERENTIAL GEOMETRY

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Abstract. We present the most important data from the biography of Prof. Dr Mileva Prvanović, the member of the Serbian Academy of Science and Arts (SANU), the first doctor of science in geometry in Serbia. Of course, this circumstance undoubtedly implies her important role in the development of this branch of mathematics. Many of results give the opportunity to confirm that her role is till now significant one. Therefore we devote this paper to analyze some of her most important results, not only in her research, but also widely.

1 Introduction

History of development of geometry in Serbia is of course a part of history of development of mathematics in Serbia. It has been considered in several monographs; one can see the newest one [Memorial 125 years of the Faculty of Mathematics, in Serbian, ed. N. Bokan, Matematički fakultet, Beograd, 1999]. This note is devoted to Prof. Dr Mileva Prvanović, the first doctor of mathematics in the branch of geometry, who is till now very active in the research and other areas. This is a great pleasure for all of us - her students and friends. We give firstly the most important data from her biography, and then we present some of her distinguished results in differential geometry. Finally we give the list of her scientific papers, published in these 50 years.

2 Some biographical data of M. Prvanović

M. Prvanović was born in 1929. She studied mathematics on the Faculty of Science, the University of Belgrade, from 1947 to 1951. She defended her doctoral thesis in Zagreb in 1955 on the Faculty of Science, the University of Zagreb.

From December 1951 to 1955 M. Prvanović was an assistant in the Mathematical Institute of SANU. From 1955 to 1993 she had a position at the University of Novi Sad, the Faculty of Science. First she was elected for an assistant, then in 1957 she became an assistant professor, in 1962 an associated professor and in 1967 a full professor. She is the member of the Serbian Academy of Science and Arts (SANU) from 1981. She was the dean of the Faculty of Science as well as an organizer of three conferences in geometry, the coeditor of proceedings of an international conference, the project leader, the chairperson of a Geometry Seminar many years in the Mathematical Institute of SANU, etc. She took care very much about her lecture for undergraduate students. Therefore she published her lecture notes to lighten accepting rather complicated topics in geometry. Her responsibility in all respects has been appreciated and recognizable by her students and colleagues.

Although she is retired from 1993, her activities are more or less the same as before, except lecturing for undergraduate students. So, she is now the editor-in-chief of the oldest journal in Serbia (and former republics of Yugoslavia): *Publications de l'Institute Mathematique.* Among activities with significant results, one can easily confirm, is her influence among students and young mathematicians who are interested in geometry, especially in differential geometry. She has pointed out permanently to her younger colleagues that it is very important to pay the attention on own permanent education and hard work; then results and papers might be natural consequences. It has been also confirmed, by her behaviour: she participated many national and international scientific meetings to communicate her results and learn new ones. She has known to assess how to help us with her experience, knowledge, literature, well developed communications with colleagues in many countries. But she knows also to appreciate our expectations and freedom. Therefore it has been really a great benefit to be a student of Prof. M. Prvanović.

She was PHD advisor of: Irena Čomić, Svetislav Minčić, Miroljub Milojević, Milan Janjić (with Prof. Dr Zagorka Šnajder), Jovanka Nikić, Nevena Pušić, Djerdji Nadj (at the University of Novi Sad); Dragoljub Cvetković and Neda Bokan (at the University of Belgrade); Kostadin Trenčevski and Ognjan Jotov (at the University of Skopje). For all these PHD candidates except M. Janjić she was also their M.Sc advisor as well as to Vojislav Petrović, Mihailo Jokić, Jan Djuras and Djordje Lisulov.

3 Mathematical activity of prof. M. Prvanović

M. Prvanović has interested in differential geometry, especially structures on manifolds and their relations with groups of transformations and corresponding invariants, recurrent spaces, geometry of connections with torsion and torsion free connections, etc. She is the author of 80 papers (for six of them - the coauthor). Complete list of papers is an appendix of this paper. To analyze all of these papers it overcomes this note. Therefore we point out the most important papers that consist the results in areas which made an influence in the research of her younger colleagues and wider.

3.1 Transformations of smooth manifolds

If we need to emphasize only one paper, as a significant one it is clearly

Holomorphically projective transformations in a locally product space, (*Mathematica balkanica*), Vol 1, pp. 195–213, (1971).

This paper was a basic one for the PHD thesis' of N. Bokan and N.Pušić, as well as for the master degree thesis of V. Petrović. This paper is also the most cited among all papers of M. Prvanović.

We present now some of results published in this paper.

Let (M^n, Γ, F) be a smooth manifold of dimension n, endowed with a torsion free connection Γ and an almost product structure ($F^2 = id$, such that $\Gamma F = 0$. She has introduced the notion of a holomorphically planar curve as a curve $x^h = x^h(t),\ h = 1, \ldots n$ whose 2-dimensional plane $(dx^h(t)/dt,\ F^h_r dx^r(t)/dt)$ is parallel along this curve with respect to the connection Γ, i.e. if this plane fulfills the equations

$$\frac{d^2x^h}{dt^2} + \Gamma^h_{ij}\frac{dx^j}{dt}\frac{dx^i}{dt} = \alpha(t)\frac{dx^h}{dt} + \beta(t)F^h_r\frac{dx^r}{dt}\,,$$

where Γ^r_{ij} are the Christoffel symbols of a connection Γ, $\alpha(t)$, $\beta(t)$ smooth functions. A holomorphically projective transformation in a locally product space (shorter HP transformation) is a transformation of torsion free connections, that preserve a holomorphically planar curve. M. Prvanović has shown that these transformations are given by

$$\bar\Gamma^r_{ij} = \Gamma^r_{ij} + (M_i\delta^r_j + M_j\delta^r_i + M_bF^b_iF^p_j + M_bF^b_jF^p_i)(\delta^r_p - \varphi F^r_p).$$

The tensor invariant with respect to HP transformations is called the HP curvature tensor. A locally product space is said to be *HP-flat* if it can be related to flat space by HP-correspondence. She proved that the locally product space is HP-flat if and only if the HP curvature tensor vanishes. Locally decomposable Riemannian spaces (spaces of a separately constant curvature) and hyperbolic Kähler spaces (spaces of an almost constant curvature) has been also considered.

Roughly speaking in the theory of transformations M. Prvanović has introduced the D-conharmonic change (a special kind of D-conformal change in a special para-Sasakian manifold), the tensor field $\mathcal{DC}$ invariant under this change and she has studied the manifolds whose tensor field $\mathcal{DC}$ vanishes.

To present these results more precisely we introduce the following notations. Let M be a manifold endowed with an almost paracontact Riemannian structure (ψ, ξ, η, g), where ψ is a field of symmetric endomorphisms of rank $n-1$, ξ a vector field, η a field of 1-forms and g a Riemannian metric satisfying the following conditions

$$\eta(\xi) = 1, \quad \psi^2 = I - \eta \otimes \xi, \quad \psi(\xi) = 0, \tag{1}$$
$$\eta \circ \psi = 0, \quad \psi\, g\, \psi = g - \eta \otimes \eta\, . \tag{2}$$

Assuming than $\psi = \nabla\xi$, where ∇ is the Levi-Civita connection for the metric g, then

$$\nabla\eta = \epsilon(-g + \eta \otimes \eta), \quad \epsilon = \pm 1.$$

An $(n-1)$-dimensional distribution D in M defined by a Pfaffian equation $\eta = 0$ is called D-distribution. D-conformal change of the structure (ψ, ξ, η, g) is given by the relations

$$^*g = e^{2\alpha}g + (e^{2\sigma} - e^{2\alpha})\eta \circ \eta \tag{3}$$
$$^*\xi = \epsilon e^{-\sigma}\xi, \quad ^*\psi = \epsilon\psi, \quad ^*\eta = \epsilon e^{\sigma}\eta \tag{4}$$

M. Prvanović has stated that $(^*\psi, {}^*\xi, {}^*\eta, {}^*g)$ is also an almost paracontact Riemannian structure and both almost paracontact Riemannian structures have the same D-distribution.

3.2 Geometry of connections with torsion

S.Minčić's PHD thesis was a prolongation of the research published in the paper

$(^1F, {}^2F)$ *and* $(^3F, {}^4F)$*-connexion of almost complex and almost product space*, (*Publication de l'Institut Math. d'Acad. Serbe des Sci.*), Vol 22(36), pp. 223–229, (1977).

In this paper M. Prvanović has studied a smooth manifold of dimension n, endowed with two connections $^1\nabla$, $^2\nabla$, that satisfy the relation:

$$^2\nabla_X Y - {}^1\nabla_Y X = [X, Y].$$

A geometry of these connections has been studied by F. Graiff (1954), E. Brinis (1957) and M. Prvanović (1959). U.P. Singh in 1959 has introduced three curvature tensors, corresponding to these connections, by the formulae

$$\begin{aligned} {}^iR(X,Y)Z &= {}^i\nabla_X\,{}^i\nabla_Y\,Z - {}^i\nabla_Y\,{}^i\nabla_X\,Z - {}^i\nabla_{[X,Y]},Z \quad i=1,2 \qquad (5)\\ {}^3R(X,Y)Z &= {}^2\nabla_X\,{}^1\nabla_Y\,Z - {}^1\nabla_Y\,{}^2\nabla_X\,Z + {}^2\nabla_{{}^1\nabla_Y X}\,Z - {}^1\nabla_{{}^2\nabla_X Y}\,Z, \qquad (6)\end{aligned}$$

S. Minčić has introduced the fourth one by the formula

$$ {}^4R(X,Y)Z = {}^2\nabla_X\,{}^1\nabla_Y\,Z - {}^1\nabla_Y\,{}^2\nabla_X\,Z + {}^2\nabla_{{}^1\nabla_Y X}\,Z - {}^1\nabla_{{}^2\nabla_X Y}\,Z\,, \qquad (7)$$

where $X,Y,Z \in \mathcal{X}(M)$. As one can see these curvature tensors introduced by using an algebraic approach to the curvature. M. Prvanović's mind to enlighten some notion from various points of view, pointing out some geometric meaning is shown wonderful, for example, just in this paper. More precisely she explained the geometric meaning of these curvature tensors in terms of parallel displacement with respect to these connections ${}^1\nabla$, ${}^2\nabla$ of a vector field v^i along a parallelogram, determined by sides dx^s, δx^s in a local chart with coordinates x^i. Consequently, she has proved that curvature tensors ${}^3R$ and ${}^4R$ are measures of difference between absolute differential as shows the picture

and the relations

$$\begin{aligned} {}^2\delta({}^1d\,v^i) - {}^1d({}^2\delta\,v^i) &= -{}^4R^i{}_{rtsv^rdx^s\delta x^t} \qquad (8)\\ {}^1\delta({}^2d\,v^i) - {}^2d({}^1\delta\,v^i) &= -{}^3R^i{}_{rts}v^r dx^s\delta x^t\,. \qquad (9)\end{aligned}$$

Among the most important results we also need to mention these ones which belong to the geometry of semi-symmetric connections. Let ${}^0\Gamma$ a symmetric affine connection, W an arbitrary tensor of type (1,2) and $O^{sh}_{ir} = \frac{1}{2}(\delta^s_i\delta^h_r + \omega F^s_i F^h_r)$, where $\omega = -1$ for an almost complex space and $\omega = +1$ for an almost product space ($F^2 = \omega$). Then

$$\Gamma^k_{ji} = {}^0\Gamma^k_{ji} + \tfrac{1}{2}\omega({}^0\nabla_j F^a_i)F^k_a + O^{ak}_{ib}W^b_{ja}$$

is a semi-symmetric connection. One can consider 4 types of the covariant derivatives ${}^i\nabla$ $i = 1, \dots, 4$ with respect to the connection Γ . So she has studied these connections in the paper

$({}^1F, {}^2F)$ and $({}^3F, {}^4F)$-connexion of almost complex and almost product space, (*Publication de l'Institut Math. d'Acad. Serbe des Sci.*), Vol 22(36), pp. 223–229, (1977).

M. Prvanović has found $({}^1F, {}^2F)$-connection: ${}^1\nabla F = {}^2\nabla F = 0$ and $({}^3F, {}^4F)$-connection: ${}^3\nabla F = {}^4\nabla F = 0$ on almost complex and almost product spaces. Moreover she has stated their interesting geometrical interpretations stating that $({}^1F, {}^2F)$-connection is the Ricca's ρ_+-connection and $({}^3F, {}^4F)$-connection is the Ricca's ρ_--connection under certain conditions.

She has introduced in the paper

Product semi-symmetric connections of the locally decomposable Riemannian spaces, (*Bull. de l'Acad. Serb. des Sci. et des Arts, Classe des Sci. math. nature*), Vol 64, No 10, pp. 17–27, (1979);

the product-semi-symmetric metric F-connection of the locally decomposable Riemannian space

$$\Gamma^i_{jk} = {}^0\Gamma^i_{jk} + S_k\delta^i_j - g_{kj}S^i + S_pF^p_kF^i_j - S^pF^i_pF_{jk},$$

where ${}^0\Gamma^i_{jk}$ are the Christoffel symbols of the Levi-Civita connection, and a product semi-symmetric recurrent connection

$$\begin{aligned} \Gamma^i_{jk} &= {}^0\Gamma^i_{jk} + S_k\delta^i_j - g_{kj}S^i + \delta^i_kM_j \\ &+ S_pF^p_kF^i_j - S^pF^i_pF_{jk} + F^i_kF^p_jM_p \end{aligned} \tag{10}$$

(not metric, but the product recurrent: $D_kg_{ij} = M_kg_{ij} + N_kF_{ij}$). A product-semi-symmetric metric F-connection is related to a product conformally flat spaces. Namely, if in a locally decomposable Riemannian space there exists a product semi-symmetric metric F-connection of zero curvature tensor, then the space is a product conformally flat.

3.3 Recurrent spaces

W. Roter and his school have interested in recurrent spaces. M. Prvanović has studied some problems in the spirit of this school. We present here some results, published in papers

On a proper conformally recurrent manifolds, (*Rad Jugoslovenske akademije znanosti i umjetnosti*), Vol 444, (*Matematičke znanosti*), No 8, pp. 137–152, (1989);

On some hypersurfaces of a recurrent Riemannian space, (*Publication de l'Institut Math.*), Vol 47(61), pp. 103–112, (1990).

Let CQR manifold be a conformally quasi-recurrent manifold. It means the covariant derivative of its Weyl conformal curvature tensor C satisfies the relations

$$\begin{aligned}(\nabla_X C)(Y,Z,V,W) &= 2a(X)\,C(Y,Z,V,W) + a(Y)\,C(X,Z,V,W) \\ &\quad + a(Z)\,C(Y,X,V,W) + a(V)\,C(Y,Z,X,W) \\ &\quad + a(W)\,C(Y,Z,V,X)\,, \quad X,Y,Z,V,W \in \mathcal{X}(M),\end{aligned} \tag{11}$$

where a is a smooth field of 1-forms. Let CR manifold be the conformally recurrent one, i.e. $\nabla C = a \otimes C$. Among relations between conformally symmetric manifold ($\nabla C = 0$), CR and CQR manifolds, studied by M. Prvanović we present these ones, stated in the following theorems.

Theorem 3.1 *If a is a gradient vector field such a manifold can be conformally related to the conformally symmetric one.*

Conversely, if a CQR manifold can be conformally related to a conformally symmetric one, and if the corresponding conformal change is of the form

$$\bar{g}_{ij} = e^{2f} g_{ij} \qquad \bar{g}^{ij} = e^{-2f} g^{ij}$$

then

- *the 1-form field a is locally a gradient and $a_i = \frac{\partial f}{\partial x^i}$;*

  item function f satisfies the condition $a(C(X,Y)Z) = 0$.

Theorem 3.2 *The necessary and sufficient condition for a CR manifold to be CQR manifold and for a CQR manifold be a CR manifold is*

$$a(X)\,C(Y,Z,V,W) + a(V)\,C(Y,Z,X,W) + a(W)\,C(Y,Z,V,X) = 0\,. \tag{12}$$

CR and CQR manifolds are also $CRQR$ manifolds (conformally recurrent and quasi-recurrent manifolds).

In the same paper examples of $CRQR$ manifolds have been constructed.

The contribution to this theory we also illustrate by the following theorem.

Theorem 3.3 *[52] Let $(\bar{M}, \bar{g})$ be a $CRQR$ manifold and let (M, g) be its totally umbilical hypersurface. If at the points of (M, g) the vector field $\hat{a}$ is not tangential to (M, g), (M, g) is conformally flat. If at the points of (M, g) the vector field $\hat{a}$ is tangential to (M, g) and (M, g) is a CQR manifold, it is a $CRQR$ manifold too.*

3.4 Algebraic structure of curvature

M. Prvanović has been interested in an algebraic structure of curvature, that was shown as a fruitful area for investigation of pointwise properties of manifolds endowed with various structures.
The most important results in this area she has published in the paper *On a curvature of Kähler type in an almost Hermitian and almost para-Hermitian manifold*, (*Mat. vesnik*), Vol 50, pp. 57–64, (1998).

She has found a tensor of Kähler type for an almost Hermitian and almost para-Hermitian manifold. This tensor is closely related with the problem of almost Hermitian and almost para-Hermitian manifold with pointwise constant holomorphic sectional curvature. Let Q be a tensor such that

$$Q(x,y,z,w) = -Q(x,y,w,z) = Q(y,x,w,z) = Q(z,w,x,y), \quad (13)$$
$$Q(x,y,z,w) + Q(z,x,y,w) + Q(y,z,x,w) = 0, \quad (14)$$
$$Q(x,y,z,w) = -\epsilon Q(x,y,Jz,Jw), \quad (15)$$

and J an endomorphism such that $J^2 = \epsilon I$ and g a metric satisfying the condition $g(Jx,Jy) = -\epsilon g(x,y)$. Then Q is a tensor of Kähler type respectively for an almost Hermitian manifold or an almost para-Hermitian manifold if $(\epsilon = 1)$ or $(\epsilon = -1)$.

Theorem 3.4 *Let (M,J,g) be an almost Hermitian (almost para-Hermitian manifold) and R its Riemannian curvature tensor. Then*

$$\begin{aligned} A(x,y,z,w) &= \tfrac{1}{16}\{3[R(x,y,z,w) - \epsilon R(x,y,Jz,Jw) & (16)\\ &\quad -\epsilon R(Jx,Jy,z,w) + R(Jx,Jy,Jz,Jw)] & (17)\\ &\quad +\epsilon[R(x,z,Jw,Jy) + R(Jx,Jz,w,y) & (18)\\ &\quad +R(x,w,Jy,Jz) + R(Jx,Jw,y,z) & (19)\\ &\quad -R(Jx,z,Jw,y) - R(x,Jz,w,Jy) & (20)\\ &\quad -R(Jx,w,y,Jz) - R(x,Jw,Jy,z)]\} & (21) \end{aligned}$$

is a curvature of Kähler type. If (M,J,g) is a Kähler (para-Kähler) manifold A reduces to the Riemannian curvature tensor.

This tensor has discovered by G. Stanilov from by using an another approach and different notations. We point out, nevertheless M. Prvanović and G. Stanilov discussed their results and have cooperated during these decades they discover recently their results coincide. Studying the pointwise Osserman conjecture in a joint paper of M. Prvanović with N. Blažić this tensor A has been crucial.

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